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Determining the Contributions in a Denim Fabric Production for Sustainable Development Goals: Life Cycle Assessment and Material Input Approaches

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Abstract: In this paper, within the framework of increasing the contributions to sustainable development goals and reducing the water footprint, the sustainable production potential of a factory producing denim fabrics have been studied in association with the sustainable development goals. For this purpose, Life Cycle Assessment and Material Input per Service methods were used to determine the environmental impact factors of the factory and the existing water footprint. Calculations were made in three different ways, taking the factory's total production capacity, a selected product, and the wet processes into account. Although the sustainable production potential of the factory is demonstrated with the Sustainable Development Goals, it has been determined that the contribution rates differ according to both the calculation method and the production data taken into account. As a result of the evaluations, it has emerged as a more dominant view that the factory's contribution to the Sustainable Development Goals should be evaluated according to the total production capacity. The sustainability evaluation made according to the total production capacity determined that the factory contributed approximately 12% to Sustainable Development Goal 12 in the period examined, according to both Life Cycle Assessment and Material Input per Service methods. Although there is inconsistency in the Life Cycle Assessment and Material Input per Service method results, it was predicted that there are economic and environmental gain potentials related to Sustainable Development Goals 13, 14, and 15, and the sustainable production potential of the factory can be increased.

Keywords: denim; sustainability; sustainable development goals; life cycle assessment; material input per service

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1. Introduction

The denim industry has recently become a sector that aims to produce by using holistic and preventive approaches that consider the entire ecosystem and profitable production and quality product targets. Although holistic and preventive approaches are expressed in different aspects, such as cleaner production, ecological production, sustainable production, green industry, and environmentally friendly technologies, the primary purpose is to ensure economic efficiency and keep the environmental impacts at a minimum level [1–4]. The primary purpose of denim production can be realized through sustainability in the broadest sense and sustainable production. The concept of sustainability, which has been developing continuously since the 1970s, was finally defined and accepted by the UNEP with the SDG main headings and subheadings, which are within the scope of the UNEP 2030 vision [5].

Accordingly, environmental issues such as sustainable cities, climate change, combating drought, and protecting biological diversity have also been on the sustainable development agenda. The 17 main objectives of the SDGs (Table 1) [6,7] are divided into three categories, taking social, economic, and environmental focuses into account.

Table 1. SDGs under three categories.

SDG	Social	SDG	Economic	SDG	Environmental
(1)	End poverty	(8)	Decent Work and Economic Growth	(6)	Clean Water and Sanitation
(2)	End hunger	(9)	Industry, Innovation, and Infrastructure	(7)	Accessible and Clean Energy
(3)	Healthy individuals	(10)	Reducing Inequalities	(13)	Climate Action
(4)	Qualified Education	(12)	Responsible Production and Consumption	(14)	Life in the water
(5)	Gender Equality	(17)	Partnerships for Goals	(15)	Life on land
(11)	Sustainable Cities and Living Spaces			(17)	Partnerships for Goals
(16)	Peace, Justice, and Strong Institutions				
(17)	Partnerships for Goals				

It is now a necessity for the denim industry, a vital industry in the world, to adopt and implement the 17 SDGs topics given in Table 1 for economic, social, and environmental reasons. Therefore, it has become essential to determine to what extent the holistic and preventive approaches applied in sustainable denim production contribute to the SDGs [8–10]. A tool that displays any SDGs and can measure the contribution rate can be used in a sustainable production assessment. However, Blackburn considered that the comprehensive assessment of a single tool is unlikely [11]. It is therefore recommended to apply a set of tools to assess the social, environmental, and economic aspects of sustainable production for a comprehensive analysis. These tools include Risk Assessment, LCA, Cost–Benefit Analysis, Ecosystem Services Assessment, Integrated Assessment Models, Sustainability Impact Assessment, MaterMIPS, Techno-Economic Analysis, The Emergy Accounting Methodology, Thermodynamic-based Measures (energy, emergy, and exergy), and Exergoenvironmental Analysis [10,12–18].

The use of LCA is a standardized method by International Organization for Standardization (ISO) orders 14040 [19] and 14044 [20] and the norms [21]. LCA comprehensively reflects the environmental impacts that may arise during the entire product or process life cycle from cradle to grave. It also ensures that the environmental impacts caused by possible changes that can be made to the product or process in question are evaluated comparatively for different scenarios and applied to the relevant decision-making processes [22–24]. The use of LCA in the denim industry has increased over the last 20 years. These studies are generally carried out to measure environmental impacts on a product basis, to determine and evaluate their footprints [25–28], and are limited to the reports prepared by denim brands and studies conducted on a specific product [4]. The lack of an integrated sustainability assessment taking the UNEP 2030 SDGs into account and not being associated with the SDGs is seen as an important deficiency in this area. Blackburn [11] states that LCA, which offers a systematic approach covering the entire production process from raw material production to the final product, is consistent with sustainability analysis and states that it is a fundamental component of the sustainability analysis due to this feature.

LCA, on the other hand, requires a large amount of data on various types of environmental emissions of inputs, outputs, and processes, which complicates the process. Although the use of standardized input–output coefficients provides an important advantage in overcoming this difficulty, it also has difficulties, such as determining system boundaries and making decisions on assumptions about future technologies [13].

The MIPS method was first published by Friedrich Schmidt-Bleek [29] to operationalize the concept and management of working at the micro, medium, and macro levels. MIPS takes into account inputs in the production and consumption system, resources from nature (including those for energy), all the material inputs and outputs (e.g., emissions and wastes), and potential impacts. The focus is on the ideas of the laws of conservation of matter and energy, which take into account quantitatively equivalent inputs and outputs. In this context, the calculation of input material flows allows a preliminary estimation of the environmental impact potential of products and businesses [30,31]. MIPS is also a practical solution to reduce the uncertainties that come with output-oriented assessments in ISO 14040/44 LCA. It was not developed to measure specific outputs (e.g., emissions of certain toxic substances) and evaluate their effects, but it is used for supports optimized multi-source input management [32,33]. Additionally, the concept of input-oriented MIPS is mostly compatible with an output-oriented LCA. As a lifecycle-wide approach, MIPS is, in many cases, equivalent to the functional unit of the LCA. Furthermore, it is a broader and more holistic approach, referring to the product service offered [10,34]. de Oliveira Neto et al. evaluated the contribution of cleaner production practices to SDGs for the Brazilian textile industry by employing the MIPS method [10]. However, such an evaluation of the denim industry, an important sub-sector of the textile industry, is quite limited in the literature.

The present study presents findings and evaluations of a project carried out within the framework of increasing the contribution of a denim fabric factory to the UNEP 2030 SDGs with clean production practices and reducing the water footprint. An integrated sustainability assessment of denim production and its relationship with SDGs is seen as an important deficiency in the literature. Additionally, there is no clear approach to which data group (total production capacity, a selected product, and wet process) will be used for the sustainability assessment of the denim industry. To eliminate this shortcoming in sustainable denim production and to clarify the subject of the data group to be used in the sustainability evaluation have been the main aim and objective of the present study. In this context, the sustainable production potential of the factory and its contribution to the SDGs in a certain period were analyzed using two different methods (LCA and MIPS) based on data from three different factories: total production capacity, a selected product, and a wet process. It is thought that the analyses and evaluations made in the study will guide the readers, researchers, and especially, denim manufacturers about associating the sustainable production potential with SDGs.

2. Materials and Methods

2.1. Materials

The present study was carried out in one of Turkey's largest integrated denim production factories established in Adana in 1951. The factory, built on an area of 200,000 square meters, employs 1350 people and has an annual denim fabric production capacity of 60×10^6 m. Approximately 85% of the denim produced is exported. Production is carried out in accordance with TS-EN-ISO 9001:2008 and TS ISO 10002: 2006 standards, and production processes have been constantly improved. Water, energy, raw materials (cotton, fiber, etc.), and chemicals (dye, acetic acid, sodium hydroxide, etc.) constitute the main inputs of denim production. The water requirement is supplied from the Adana Organized Industrial Zone treatment plant. The energy need is met by electricity, natural gas cogeneration plant (approximately 40%), and solar panels (approximately 7%). Although the raw materials used in production are generally domestically produced, some of them are also imported. The chemicals used in the production processes are procured from approved suppliers.

2.2. Methods

A literature review was carried out to determine the appropriate method to examine the current sustainable production potential of the factory and its contribution to the

SDGs. In the literature review, it was determined that reports on sustainability assessments are generally prepared based on different data and methods [10,35,36]. Therefore, the sustainable production potential of the denim factory and its contribution to SDGs were analyzed by employing the 2017 and 2019 data, the LCA and MIPS methods, the total production capacity, a selected product, and the wet process basis.

2.2.1. Life Cycle Assessment (LCA)

For the assessment of sustainable production with LCA, the software program "PRé-Consultant, 2018, SimaPro Life Cycle Assessment Software Package, Version 8.5.2, Amsterdam, The Netherlands" was utilized. SimaPro has been reported as one of the two leading software applications worldwide for LCA studies and is an ISO-compliant software used in many fields in more than 80 countries [36]. Simapro developed by PRé Sustainability is widely used to analyze and report the sustainability performance of products and services, to calculate the carbon footprint, water footprint, and environmental impact results, and to identify and monitor key performance indicators [37].

For LCA, denim production was simulated using both the consumption and production data from the factory (primary) and corresponding data from the CML-IA database (secondary). CML-IA used to perform the simulation is an LCA methodology developed by the Center for Environmental Sciences (CML) at Leiden University in the Netherlands. This method is an update of CML 2 base 2000 and corresponds to files (version 4.7) released by CML in August 2016. Then, the environmental impacts to be calculated based on the concept of "cradle to grave" were selected for denim production. The LCA calculation process is given in Figure 1 [23], and the 14 selected impact categories are given in Table 2.

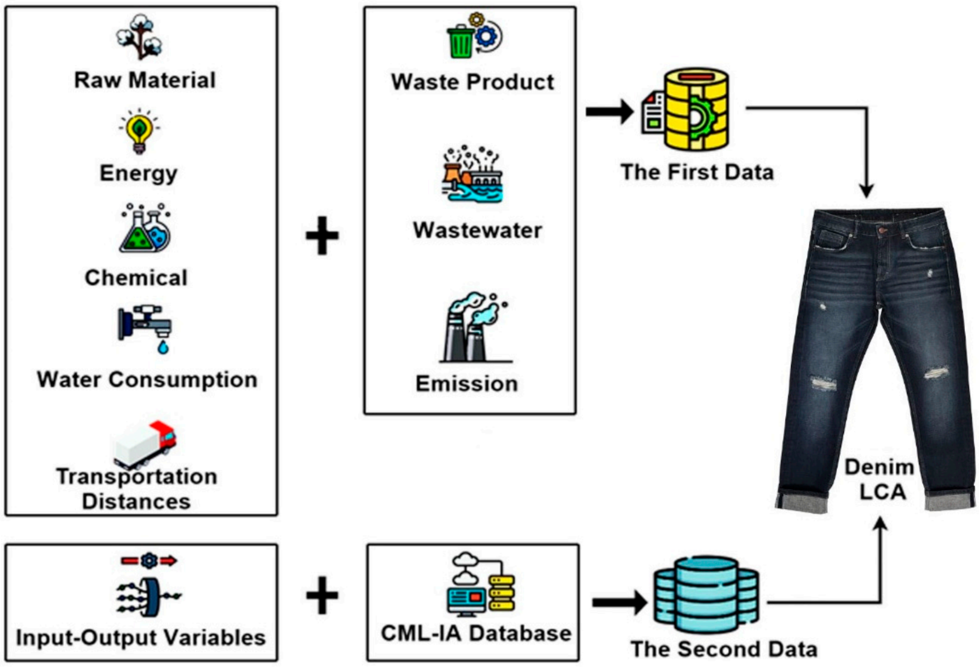

Figure 1. Diagram showing the LCA calculation process.

Table 2. Selected LCA Impact Categories.

Impact Category	Unit
Abiotic depletion (elements and final reserves)	kg Sb eq
Abiotic depletion (fossil fuels)	MJ
Global warming (GWP100a)	kg CO_2 eq
Ozone layer depletion (ODP)	kg CFC-11 eq
Human toxicity	kg 1,4-DB eq
Freshwater aquatic ecotox.	kg 1,4-DB eq

Table 2. *Cont.*

Impact Category	Unit
Marine aquatic ecotoxicity	kg 1,4-DB eq
Terrestrial ecotoxicity	kg 1,4-DB eq
Photochemical oxidation	kg C_2H_4 eq
Acidification	kg SO_2 eq
Eutrophication	kg PO_4 eq
Total Water Use	m^3
Total Water Use (life cycle group)	UBP
Total Water Use (Hoekstra)	m^3

2.2.2. Material Input per Service of Unit (MIPS)

MIPS was preferred as a second method to analyze the factory's sustainable production potential and its contribution to the SDGs. The reason for choosing MIPS is that it has been used by many researchers, and remarkable results have been obtained [10,12,38]. Basic Equation (1) used for the MIPS calculation is given below [29,34,39].

$$\text{MIPS} = \frac{\text{MI}}{\text{S}} \quad (1)$$

In Equation (1), MI is defined as a material input and S is defined as a service unit. This equation explains the rate of use of primary material (natural resource) in production by a business. Although it has been stated that MIPS is measured in kg per service unit [38], it has been reported that there is no fixed size for the units in the method, and the unit size can be determined according to the type and variety of the product delivered to the factories [34]. MIPS, which is developed by the Wuppertal Institute (Germany) and is capable of assessing environmental changes associated with resource extraction, is a measure of natural resources used throughout the entire life cycle (resource extraction, production, transport, packaging, operation, reuse, recycling, and remanufacturing, and waste disposal) [40,41]. Measured in kg per unit of service [38], MIPS consists of the sum of individual calculations of five environmental impact categories (abiotic, biotic, erosion, air, and water) [41]. The MIPS calculations made in this study were made using Equation (2) [10].

$$\text{M} = (\text{Massx MIF}_{\text{abiotic}}) + (\text{MassxMIF}_{\text{biotic}}) + (\text{MassxMIF}_{\text{erosion}}) + (\text{MassxMIF}_{\text{air}}) + (\text{MassxMIF}_{\text{water}}) \quad (2)$$

In Equation (2), MIT is defined as the total material density, and MIF is defined as the mass density factor of the category. In the calculation, the consumed amounts of the inputs in the production process were determined separately for biotic, abiotic, erosion, water, and air environmental impact factors for 2017 and 2019. The amounts consumed were multiplied by the density factors (MIF) defined by the Wuppertal Institute [41], the mass densities per compartment (MIC/Mass Intensity per Compartment) were calculated for each environmental impact factor, and the MIT values were found by adding these compartment densities. Then, the MIPS values were calculated by dividing the MIT values by the service (S).

3. Results and Discussion

It is important to specify the limitations and delimitations of the study in terms of the reproducibility and reliability of the findings, analyses, and results obtained in the present study and to guide similar future studies. One of the theoretical limitations of the research is that the literature directly related to the examined subject is not sufficient. The methodological limitations include the fact that the working period is carried out in a period when new social, economic, and environmental changes occur in society, such as COVID-19, inadequacies in recording and documentation in collecting retrospective data, incomplete records in the factory, some data are obtained based on verbal statements, and the nondisclosure of some data (for example, product recipes) within the scope of the privacy policy. Additionally, the LCA software, its interface, impact categories, and database should be considered in terms of association in future studies. The delimitations set by the authors in the study should also be taken into account by the readers. The study was conducted for a denim factory operating in Turkey and was carried out using only data from 2017 and 2019. To reveal the contribution of the factory to the SDGs in the specified period, LCA and MIPS were used. The data used in the study were obtained from the records of the relevant units of the denim factory. Reliability, Risk Assessment, and uncertainty analyses related to the data could not be performed. The improvement in the sustainable production potential of the denim production facility was examined on the basis of total production capacity, a selected product, and the wet process. The analyses and evaluations made are presented below.

3.1. Sustainability Assessment Based on "Total Production Capacity"

Many chemicals and dyes have been known to be used in denim production, as well as raw materials, water, and energy. Additionally, these inputs and their amounts vary on the basis of the product and process. Since it was not possible to fully evaluate this large number and the amount of inputs in the "total production capacity-based" sustainability assessment, besides cotton, water, and energy consumption, chemicals with an annual consumption of 10 tons or more were taken into account. In this context, the resource data consumed for 1 ton of fabric production in 2017 and 2019 are given in Table 3.

Table 3. Resources consumed for the production of 1 ton of fabric.

Material	Unit	2017	2019
Total fabric produced/year	ton	13,069,514.00	17,400,000.00
Cotton	kg	1175.00	1175.00
Electric	kWh	654.71	619.51
Natural gas	MJ	29,330.20	24,270.72
Sodium hydroxide, without water, in a 50% solution state	kg	468.31	457.02
Diresul Black RDT M, Sulfur, Chemical, inorganic	kg	77.90	58.14
Acetic acid, without water, in 98% solution state	kg	58.08	56.20
Indigo, INDIGO	kg	27.96	37.13
Antioxidant B	kg	24.98	-
Prosize AFN, Starch Maize starch	kg	19.31	47.80
Hydrosulfide Sodium hydrosulfide	kg	15.50	19.28
Organic Chemistry	kg	36.00	88.10
Chemical, inorganic	kg	18.07	-
Oxidante Bri	kg	8.09	11.37
Saquest FCT, Ion Sequestrant, Phosphoric acid	kg	6.07	7.11
Arkofil CO, Acrylic acid	kg	5.41	9.15
Optisize, Vinyl Acetate Vinyl acetate	kg	3.56	2.63
Belsoft 300, Fatty alcohol sulfate	kg	3.23	2.62
DNG Blue Notear (Resinblue), Acrylic Polymer	kg	3.00	1.25
Hydrogen peroxide	kg	2.91	4.36
Antioxidant M	kg	2.41	-
Sodium sulfate, anhydrite	kg	1.79	1.38
Cerat 985, Wax, lost-wax casting	kg	1.62	1.95
Sodium silicate, solid	kg	1.57	1.04
Sodium hypochlorite, without water, in a 15% solution state	kg	1.52	1.30

Table 3. *Cont.*

Material	Unit	2017	2019
Floranit 40/2B, Ethoxylated alcohol	kg	1.51	1.65
Soda ash, light, crystalline, heptahydrate	kg	1.38	0.76
Evo Fin PE, Wax, lost-wax casting	kg	1.05	-
Rucofin MES, Silicone product	kg	0.85	-
Setalan SW Dispergator, Naphthalene sulfonic acid	kg	0.80	0.77
Colorsize IQ Size, Acrylic Polymer	kg	0.79	0.64
Cottoclorin Arrow Dispergator	kg	0.70	0.57
Belfoft EG, Fatty alcohol sulfate	kg	0.64	-
Expanded perlite	kg	0.62	-
Alfalina PRM New, Silicone product	kg	-	0.69
Antioxidant M	kg	-	2.88
Antioxidant BB	kg	-	31.92
Arkofil CO, Methanol	kg	-	1.18
Benzyl alcohol	kg	-	0.75
Cerofil LF, Wax, lost-wax casting	kg	-	1.78
Denimblue 30, INDIGO	kg	-	1.13
Optisize, Vinyl Acetate Vinyl acetate	kg	-	1.43
Optisize WX-B, Wax, lost-wax casting	kg	-	0.67
Product RD 462, Acrylic Polymer Acrylic dispersion	kg	-	11.36
Product RD 611, Acrylic Polymer	kg	-	0.66
Sodium chloride powder	kg	-	9.02
Rucowet DWA, Alkylbenzene sulfonate, linear	kg	-	2.88
Serawet M-BK wetting agent, Ethylene glycol	kg	-	2.91
Waste Water Amount (for the total factory)	m^3	2,080,090.00	2,312,891.00
BOD_5	kg	570,627.70	673,143.80
COD	kg	2,282,690.77	2,692,598.30

3.1.1. LCA Evaluation Based on "Total Production Capacity"

LCA calculation results for selected environmental impact factors of "total production capacity-based" inputs are given in Table 4. Calculations were made using SimaPro software, the CML-IA basic database, and the EU25 normalization method.

Table 4. "Total production capacity-based" LCA results.

Impact Category	Unit	2017	2019
Abiotic depletion (elements, final reserves)	kg Sb eq	2.81×10^{-5}	2.49×10^{-5}
Abiotic depletion (fossil fuels)	MJ	112	143
Global warming (GWP100a)	kg CO_2 eq	8.20	7.50
Ozone layer depletion (ODP)	kg CFC-11 eq	1.53×10^{-6}	1.65×10^{-6}
Human toxicity	kg 1.4-DB eq	3.11	2.92
Freshwater aquatic ecotox.	kg 1.4-DB eq	30.40	26.30
Marine aquatic ecotoxicity	kg 1.4-DB eq	7.33×10^{3}	6.54×10^{3}
Terrestrial ecotoxicity	kg 1.4-DB eq	2.21	1.90
Photochemical oxidation	kg C_2H_4 eq	0.0022	0.0023
Acidification	kg SO_2 eq	0.0556	0.0545

Table 4. *Cont.*

Impact Category	Unit	2017	2019
Eutrophication	kg PO_4 eq	0.0246	0.0212
Total Water Use	m^3	2.96	2.54
Total Water Use (life cycle group)	UBP	803	691
Total Water Use (Hoekstra)	m^3	1.32	1.13

By considering the results in Table 4, it can be argued that the inputs that are most effective on the sustainable production potential of the denim factory are raw materials (cotton), energy (electricity), and chemicals (sodium hydroxide, sodium hydrosulfite, starch, and dyestuff). It was seen that the factory had improved its performance in sustainability in 2019 compared to that in 2017, including all the impact factors except for the abiotic depletion (fossil fuels) and ozone layer depletion (ODP) environmental impact factors. The following results were obtained in the evaluations made by associating the "total production capacity-based" LCA calculation results of the factory with the UNEP 2030 SDGs:

- SDG 12, Responsible Production and Consumption: The factory has achieved an 11.4% improvement in managing natural resources, reducing waste and pollutants, and ensuring their final disposal.
- SDG 13, Climate Action: In the fight against climate change and its effects, positive improvements were achieved in some sub-headings (+8.5% in global warming), whereas there was a lack of improvements in some sub-headings (−27.67% in abiotic depletion-fossil fuels and −7.8% ozone layer depletion were observed).
- SDG 14, Life in Water: In terms of managing marine and coastal ecosystems sustainably, protecting them from pollution, and investigating the effects of ocean acidification; +13.5%, +10.7%; +1.97%, and +13.8% recovery rates were achieved for freshwater ecotoxicity, marine aquatic ecotoxicity, acidification, and eutrophication, respectively.
- SDG 15, Terrestrial Life: Plant improvements in 2017 and 2019 are aimed at protecting and restoring terrestrial ecosystems such as forests, wetlands, drylands, and mountains, combating desertification, stopping and reversing land degradation, and halting biodiversity loss. Accordingly, a +14% contribution was gained.
- As seen in the "total production capacity-based" LCA calculations and the UNEP 2030 SDG assessments of the denim factory, it can be argued that improvements were made in terms of raw materials, chemicals, and water consumption for 2017 and 2019 within the scope of sustainable production, and these contribute to SDGs 12, 14, and 15. However, arguing that sustainable production is realized within the scope of SDG 13 due to the increase in the use of natural gas for cogenerator purposes in the factory during the period taken into account is not possible. It is thought that this is important in terms of determining cleaner production opportunities and focal points in the factory. Cleaner production practices are one of the important tools of sustainable production and contribution to the SDGs [42].

3.1.2. MIPS Evaluation Based on "Total Production Capacity"

The results of the MIPS calculations using "total production capacity-based" input values are given in Table 5. A comparison of the sustainable production potentials of the factory calculated with the MIPS method between the years 2017 and 2019 is presented in Figure 2.

Table 5. "Total production capacity-based" MIPS results.

	Unit	Abiotic Depletion	Biotic Depletion	Erosion	Water	Air
2017	kg/kg	54,772.45	3407.50	5886.75	8255.64	4169.40
2019	kg/kg	48,251.58	3407.50	5886.75	8231.81	4128.75
Change	%	11.91	0.00	0.00	0.29	0.98

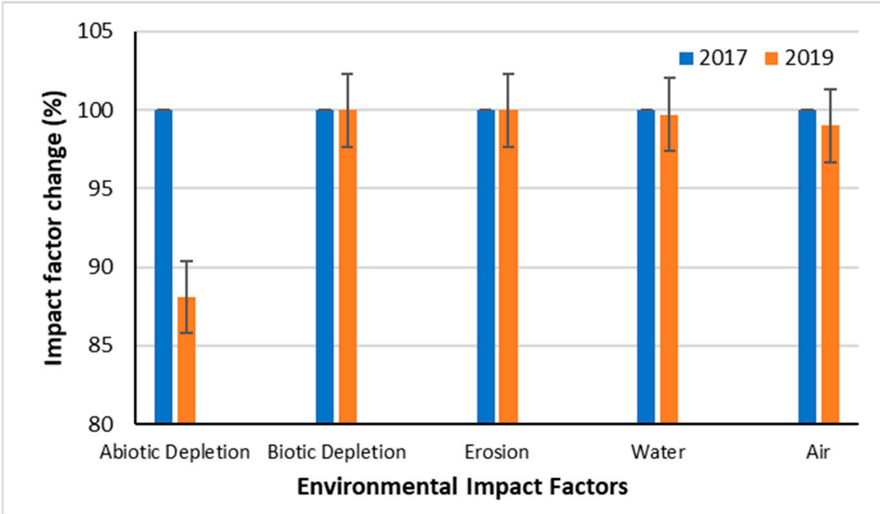

Figure 2. Sustainability comparison for the years. 2017 and 2019, according to "total production capacity-based" MIPS calculations.

As seen in Table 5 and Figure 2, the results obtained in the evaluations made of the factory's "total production capacity-based" MIPS calculations in association with the UNEP 2030 SDGs are as follows:

- SDG 12: There was a +11.91% improvement in the scope of abiotic consumption environmental impact factor.
- In SDG 13: The air environmental impact factor had a slight improvement of +0.98%.
- SDG 14: There was a slight improvement of +0.29% in the water environmental impact factor. Since the inputs (raw materials, chemicals, and other resources) used in denim production are variable according to the product type and the effect of the type, the difference cannot be determined. No changes were observed in the environmental impact factors such as biotic consumption and erosion in the MIPS calculations. Zamcopé et al. [35] stated that the inputs used in the production of different product types are very variable. Therefore, the effect of type differences on the results could not be determined. In this respect, the MIPS assessment used for the "total production capacity-based" sustainable production potential of the factory is likely to reduce the deviations that may occur due to the excess product variety in the enterprise.

3.2. Sustainability Assessment Based on a "Selected Product"

To determine and evaluate the sustainable production potential of the factory based on a "selected product," "FX Revolve Black OD Black" was chosen as the most produced product type in 2017 and 2019. The production volumes of this product type in 2017 and 2019 were 408.72 and 769.65 tons, respectively. The inputs used in the production process of "FX Revolve Black OD Black" are given in Table 6.

Table 6. Resources consumed for the production of 1 ton of "FX Revolve Black OD Black".

Material	Unit	2017	2019
Type production	ton	408.72	769.65
Cotton	kg	1175.00	1175.00
Electric	kWh	99,028.51	118,668.90
Natural gas	MJ	1.40	1.06
Sodium hydroxide	kg	87,650.20	165,053.20
Floranit 40/2B, Ethoxylated alcohol (AE11)	kg	1255.86	2364.90

Table 6. *Cont.*

Material	Unit	2017	2019
Saquest FCT, Ion Sequestrant, Phosphoric acid	kg	1912.15	3600.75
Antioxidant B, Chemical, inorganic	kg	6037.14	11,368.48
Rucowet DWA, Alkylbenzene sulfonate	kg	1837.43	3460.04
Acetic acid	kg	24,003.60	45,200.98
Prosize AFN, Starch Maize starch	kg	24,107.16	45,395.94
Optisize, Vinyl Acetate	kg	4767.77	8978.15
Cerat 985, Wax	kg	1324.28	2493.74
Antioxidant BB, Chemical, inorganic	kg	18,009.70	33,913.88
Diresul Black RDT M, Sulfur	kg	15,335.03	28,877.23
Organic Chemistry, Chemical	kg	81,454.62	153,386.30
Water, decarbonized	kg	71,660,636.00	1.13×10^8

3.2.1. LCA Evaluation Based on a "Selected Product"

The values of the environmental impact categories calculated using the inputs "based on a selected product" and the applied LCA are given in Table 7.

Table 7. "Based on a selected product" LCA results.

Impact Category	Unit	2017	2019
Abiotic depletion (elements, final reserves)	kg Sb eq	2.05×10^{-5}	2.05×10^{-5}
Abiotic depletion (fossil fuels)	MJ	55.90	55.90
Global warming (GWP100a)	kg CO_2 eq	4.44	4.43
Ozone layer depletion (ODP)	kg CFC-11 eq	9.24×10^{-7}	9.24×10^{-7}
Human toxicity	kg 1.4-DB eq	2.08	2.07
Freshwater aquatic ecotox.	kg 1.4-DB eq	28.10	28.10
Marine aquatic ecotoxicity	kg 1.4-DB eq	4.43×10^3	4.43×10^3
Terrestrial ecotoxicity	kg 1.4-DB eq	2.09	2.09
Photochemical oxidation	kg C_2H_4 eq	0.00124	0.00124
Acidification	kg SO_2 eq	0.0334	0.0324
Eutrophication	kg PO_4 eq	0.0153	0.0153
Total Water Use	m^3	2.81	2.77
Total Water Use (life cycle group)	UBP	761	758
Total Water Use (Hoekstra)	m^3	1.25	1.23

Table 7 shows that the environmental impact category values given in the LCA results are very similar to each other for 2017 and 2019. It is seen that there are very low reductions of the environmental impact categories such as total water consumption, acidification, human toxicity, and global warming. In this case, revealing the sustainable production potential with the LCA results "based on a selected product" in association with the SDGs and contribution rates cannot be considered as a healthy approach. This is because the inputs based on a "selected product" do not substantially change in the production process depending on time. Therefore, non-significant changes in the number or amount of inputs do not make a significant contribution to the sustainable production potential. According to the LCA results given in Table 7, the factory achieved a very small improvement during the specified period in the UNEP 2030 SDGs 13 and 14, which are +0.2% and +0.1%, respectively, cotton, starch, organic materials, sodium hydroxide, and acetic acid were determined to be the most important inputs affecting the sustainable production potential of the factory based on a selected product.

3.2.2. MIPS Evaluation Based on "Selected Product"

The results of MIPS calculations for 2017 and 2019 using inputs based on a "selected product" are presented in Table 8, and a comparison of the sustainable production potentials is presented in Figure 3.

Table 8. "Based on a selected product" MIPS results.

	Unit	Abiotic Depletion	Biotic Depletion	Erosion	Water	Air
2017	kg/kg	15,032.21	3407.50	5886.75	8,049,087.62	3584.87
2019	kg/kg	15,608.81	3407.50	5886.75	8,051,025.41	3614,32
Change	%	−3.84	0.00	0.00	−0.02	−0.82

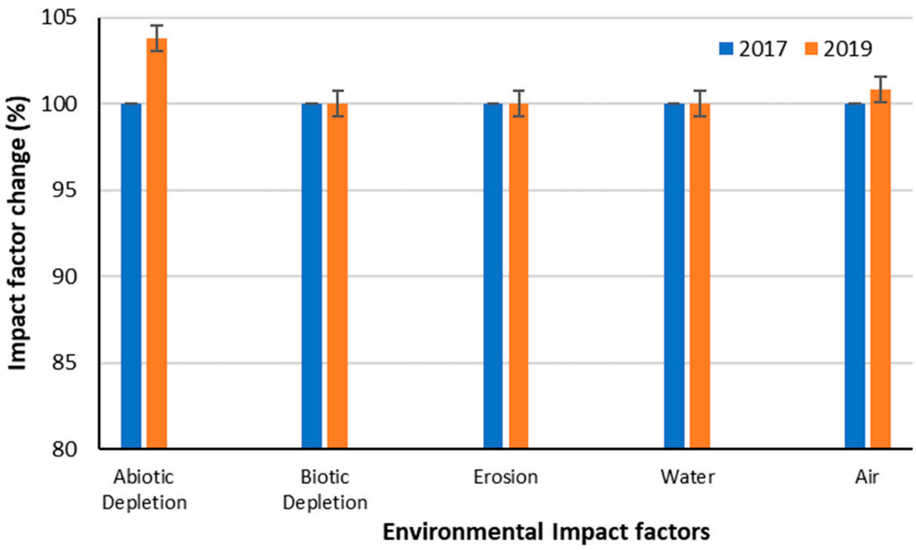

Figure 3. Sustainability comparison for 2017–2019 according to MIPS calculations "based on a selected product".

The MIPS results "based on a selected product" given in Table 8 are −3.84%, −0.82%, and −0.02% for the environmental impact factors, abiotic consumption (SDG 12), air (SDG 13), and water (SDG 14), respectively. The small changes can be explained by the absence of significant changes in the years specified in the prescription of the selected product: "FX Revolve Black OD Black". For abiotic consumption and air impact factors, if the change is negative, the increase in fossil fuel use may be due to loss and leakage for the water impact factor.

3.3. Sustainability Assessment Based on "Wet Process"

The water-, energy-, and chemical-intensive "warp yarn sizing and dyeing process" in the denim production process were chosen to calculate the "wet process-based" sustainable production potential of the factory and to associate it with the SDGs. The inputs of the selected wet process in 2017 and 2019 are given in Table 9.

Table 9. Resources consumed for 1 ton of product "based on wet process".

Material	Unit	2017	2019
Cotton	kg	1000.00	1000.00
Water	m^3	86.00	54.93
Hydroxide, without water, in a 50% solution state	kg	813.42	457.02

Table 9. *Cont.*

Material	Unit	2017	2019
Diresul Black RDT M, Sulfur, Chemical, inorganic	kg	135.31	58.4
Indigo, INDIGO	kg	48,57	37.13
Antioxidant B, Chemical, inorganic	kg	43.40	-
Prosize AFN, Starch Maize starch	kg	33.54	47.80
Hydrosulfite, Sodium hydrosulfide	kg	26.92	19.28
Saquest FCT, Ion Sequestrant, Phosphoric acid	kg	10.54	7.11
Arkofil CO, Acrylic acid	kg	9.40	9.15
Optimize, Vinyl Acetate	kg	6.19	2.63
Antioxidant M, Chemical, inorganic	kg	4.19	2.88
Sodium sulfate, anhydrite	kg	3.11	-
Cerat 985, Wax, lost-wax casting	kg	2.82	1.95
Floranit 40/2B, Ethoxylated alcohol (AE11)	kg	2.62	1.65
Evo Fin PE, Wax, lost-wax casting	kg	1.83	-
Setalan SW Dispergator, Naphthalene sulfonic acid	kg	1.40	0.77
Colorsize IQ Size, Acrylic Polymer	kg	1.37	0.64
Cottoclorin Arrow Dispergator, Naphthalene sulfonic acid	kg	1.22	0.57
Water, decarbonized	kg	85,996.39	37,887.7
Natural gas, liquefied	m^3	205.57	1051.48
Electricity, high voltage	kWh	23.43	10.73
Alfalina PRM New, Silicone product	kg	-	0.69
Antioxidant BB, Chemical, inorganic	kg	-	31.92
Arkofil CO, Methanol	kg	-	1.18
Cerofil LF, Wax, lost-wax casting	kg	-	1.78
Optisize, Vinyl Acetate Vinyl acetate	kg	-	1.43
Optisize WX-B, Wax, lost-wax casting	kg	-	0.67
Rucowet DWA, Alkylbenzene sulfonate, linear, petrochemical	kg	-	2.88
Serawet M-BK wetting agent, Ethylene glycol	kg	-	2.91

3.3.1. LCA Evaluation Based on "Wet Process"

The LCA results obtained using the factory's "wet process"-based inputs (Table 9) are given in Table 10 for each environmental impact category.

Table 10. LCA results based on "wet process" L.

Impact Category	Unit	2017	2019
Abiotic depletion (elements, final reserves)	kg Sb eq	2.72×10^{-5}	2.59×10^{-5}
Abiotic depletion (fossil fuels)	MJ	58.1	120
Global warming (GWP100a)	kg CO_2 eq	4.62	5.28
Ozone layer depletion (ODP)	kg CFC-11 eq	1.25×10^{-6}	9.58×10^{-7}
Human toxicity	kg 1,4-DB eq	2.09	2.31
Freshwater aquatic ecotox.	kg 1,4-DB eq	24.40	24.50
Marine aquatic ecotoxicity	kg 1,4-DB eq	5.24×10^{3}	5.34×10^{3}
Terrestrial ecotoxicity	kg 1,4-DB eq	1.79	1.79
Photochemical oxidation	kg C_2H_4 eq	0.00122	0.00172
Acidification	kg SO_2 eq	0.0348	0.0441
Eutrophication	kg PO_4 eq	0.0151	0.015
Total Water Use	m^3	2.35	2.31
Total Water Use (life cycle group)	UBP	644	641
Total Water Use (Hoekstra)	m^3	1.04	1.02

From the LCA results given in Table 10, it can be seen that some of the environmental impact factors values in 2019 improved compared to those in 2017, whereas some did not. For example, an improvement was observed in the abiotic consumption factor (elements and final reserves), whereas a lack of improvement was observed in abiotic depletion (fossil fuels), global warming, ozone layer, human toxicity, freshwater, marine, aquatic and terrestrial ecotoxicities, photochemical oxidation, and acidification effect factors. In the present study, environmental impact headings were evaluated as being cleaner production opportunities and focal points. According to the results of the "wet process-based" LCA, it is only possible to consider its contribution to UNEP 2030 SDG 12. The inputs that affect the sustainable production potential of the factory are cotton, sodium hydroxide, sodium hydrosulfite, natural gas, starch, and dyestuff. The substitution of inputs with a high environmental impact factor with inputs with a lower impact factor [43] is presented here as a solution proposal. More ecological substitutes have been reported to contribute to SDGs 9, 12, and 15 [10].

3.3.2. MIPS Evaluation Based on "Wet Process"

In the denim sector, the processes in which raw materials, chemicals, water, and energy are used most intensively are the processes that include sizing, dyeing, and washing processes, which are called "wet processes" [36]. These processes have an important potential in terms of increasing the sustainable production potential and realizing cleaner production practices. As seen in Table 11 and Figure 4, improvements in abiotic consumption, water, and air environmental impact factors were recorded in the MIPS calculations for 2017 and 2019. No changes were seen in the biotic depletion and erosion factors. The most significant improvements under the UNEP 2030 SDGs were achieved for SDG 12 (+12.68%), SDG 13 (+7.8%), and SDG 14 (+0.69%). Reducing resource consumption or substitution is an important factor for sustainable production, and it also provides an opportunity to generate less waste. The reason why no changes were observed in biotic consumption and erosion environmental impact factors in Table 11 and Figure 4 is that inputs such as chemicals, water, and energy vary according to the type of product processed in the "wet process", and, therefore, the type difference effect cannot be determined.

Table 11. MIPS results based on "wet process".

	Unit	Abiotic Depletion	Biotic Depletion	Erosion	Water	Air
2017	kg/kg	54,772.46	3407.50	5886.75	8,120,075.90	4169.40
2019	kg/kg	48,251.58	3407.50	5886.75	8,118,303.96	4128.75
Change	%	12.86	0.00	0.00	0.69	7.38

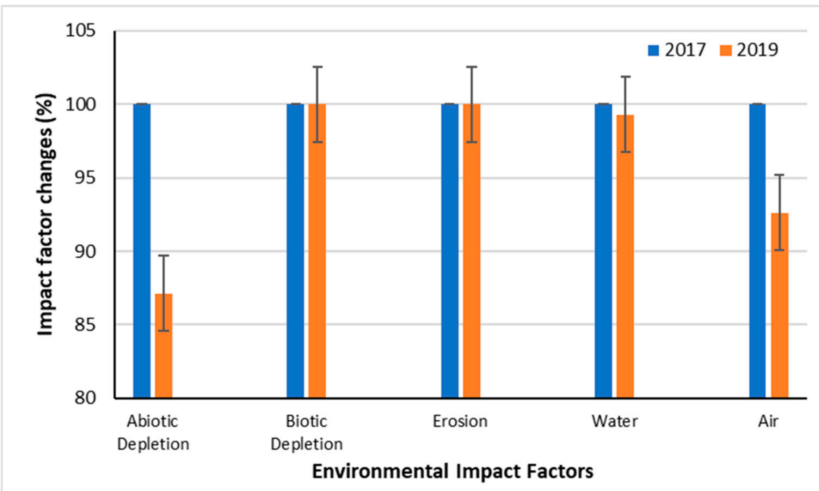

Figure 4. Sustainability comparison for 2017–2019 according to MIPS calculations "based on wet process".

3.4. General Evaluations

The factory's contribution rates to the UNEP 2030 SDGs are given in Tables 12 and 13 for the LCA and MIPS methods, respectively.

Table 12. Facility contribution to the UNEP 2030 SDGs according to LCA.

UNEP 2030 SDGs	Environmental Impact Factor	Based on the Total Production Capacity (%)	Based on a Selected Product (%)	Based on the Wet Process (%)
12	Abiotic depletion (elements, final reserves)	11.40	0	4.77
	Abiotic depletion (fossil fuels)	−27.67	0	−106
13	Global warming (GWP100a)	8.50	0.2	−14. 28
	Ozone layer depletion (ODP)	−7.80	0	23.36
14	Freshwater aquatic ecotox.	13.50	0	−0.40
	Marine aquatic ecotoxicity	10.70	0	−1.90
	Acidification	1.97	0.1	−26.72
	Eutrophication	13.80	0	0
15	Terrestrial ecotoxicity	14	0	0

Table 13. Facility contribution to the UNEP 2030 SDGs according to MIPS.

UNEP 2030 SDGs	Environmental Impact Factor	Based on the Total Production Capacity (%)	Based on a Selected Product (%)	Based on the Wet Process (%)
12	Abiotic Depletion	11.91	−3.84	12.86
13	Air	0.98	−0.82	7.38
14	Water	0.29	−0.02	0.69
15	Erosion	0	0	0

As seen in Tables 12 and 13, there are differences in both the LCA and MIPS sustainability assessments in terms of both the SDGs that were contributed to and the contribution rates. These differences stem from both the factory data taken into account to determine sustainable production potential and some conceptual divergences between LCA and MIPS.

In assessing LCA and MIPS based on "total production capacity", "a selected product", and "wet process", the "total production capacity-based" approach is recommended for more comprehensive and reliable, sustainable production. By considering the positive values according to the compatible aspects of both approaches, it was seen that the factory provides an improvement of approximately 11–12% for UNEP SDG 12 and increases its sustainable production potential. There is an inconsistency between the contribution rates for SDGs 13, 14, and 15. This inconsistency was associated with conceptual differences. An example of this conceptual difference is that the MIPS abiotic environmental impact factor represents the total used and unused resource extraction, whereas the LCA abiotic one (elements and final reserves) only takes some metal inputs into account. In the calculations "based on a selected product" by LCA and MIPS, the absence of significant changes in the product recipes depending on time, that is, the unchanged input types and amounts, did not cause a significant change in the values of the environmental impact factors. Although the sizing and dyeing processes, which are processes with high chemical, water, and energy consumption, are chosen in the "wet process-based" evaluation, it was thought that these were not the right choices to determine the sustainable production potential of the factory. This is because in this approach, the energy-intensive parts of the factory, such as yarn and weaving, are not taken into account. Although water and energy savings were achieved with the changes made in the dyeing methods (transition to the Save Blue method) and steam recovery methods (transition to the Flash Steam method) in the examined period, it is thought that the increase in the use and amount of fossil fuels in cogeneration negatively affects the sustainable production potential.

In the present study, it was also important to determine which parameters the sustainable production potential of the denim industry is more sensitive to. Electricity, water, natural gas, cotton, and dye-chemical consumptions were determined as variables. Each independent parameter was changed proportionally (±25, 50%), and the differences in the change from the original scenario were calculated by leaving the remaining data in the new scenarios designed [44,45]. It was determined that the rate of changes in the environmental impact parameters decreased and increased linearly ($R^2 = 1$). By proportionally increasing the parameters by 25%, the resulting percentage changes in the environmental impacts are given in Table 14.

Table 14. Sensitivity analysis results. (Dark green, green, light green, yellow, light orange, dark orange and red color transitions indicate the numerical increase in the sensitivity analysis).

	Environmental Impact Percentage Change											
Input Source	**Abiotic Depletion (kg Sb eq)**	**Abiotic Depletion (Fossil Fuels) (MJ)**	**Global Warming (GWP100a) (kg CO_2 eq)**	**Ozone Layer Depletion (ODP) (kg CFC-11 eq)**	**Human Toxicity (kg 1,4-DB eq)**	**Freshwater Aquatic Ecotox. (kg 1,4-DB eq)**	**Marine Aquatic Ecotoxicity (kg 1,4-DB eq)**	**Terrestrial Ecotoxicity (kg 1,4-DB eq)**	**Photochemical Oxidation (kg C_2H_4 eq)**	**Acidification (kg SO_2 eq)**	**Eutrophication (kg PO_4^{3-} eq)**	**Total Water Use (m^3)**
Electricity	0.66	9.18	8.72	0.92	6.95	0.85	11.79	0.05	7.90	6.83	7.57	0.10
Natural gas	0.07	3.09	2.10	1.82	0.25	0.02	0.26	0.00	0.91	0.40	0.17	0.02
Water	0.56	0.64	0.65	0.39	0.80	0.21	1.11	0.02	0.83	0.46	0.46	5.48
Coton	18.62	6.81	9.55	11.35	12.78	23.56	7.06	24.84	9.43	13.30	14.78	19.24
Dye chemicals	4.25	3.16	2.67	9.20	3.20	0.31	3.74	0.08	4.58	3.17	1.63	0.13

By examining Table 14, it is seen that environmental impact parameters in the denim sector are primarily sensitive to the increase in cotton consumption, followed by electricity and dye chemical consumption, respectively. The increases in the cotton consumption, abiotic depletion (elements and final reserves), freshwater aquatic ecotoxicity, terrestrial ecotoxicity, and total water use environmental impact categories were 25%, 24.84%, 23.56, 19.24, and 18.62%, respectively. These results obtained by sensitivity analysis are also consistent with the literature [4,46]. According to these results, the cotton used as a raw product material and the spinning process that uses electricity the most can be shown as the most important sources of the environmental impact in denim production.

The LCA and MIPS sustainability assessment methods used for determining the contribution to UNEP 2030 SDGs in denim production did not produce consistent results among each other, except for SDG 12. It can be argued that both methods have both advantages and disadvantages, especially conceptual differences. Aghbashlo et al. [18] stated that although each of the sustainability assessment methods seems to be a powerful tool, they cannot produce optimal solutions, and sustainability assessment tools should be integrated for optimal solutions, and this integration will improve the methods. The results in the present study support those reported by Aghbashlo et al. [18]. However, they showed that there is a need for research and development for an integrated and standardized sustainability assessment method for the denim industry. The results of the extensive and state-of-the-art literature review presented by Backes and Traverso [47] also confirm this necessity. The need to combine sustainability assessment tools and SDGs is evident from the increasing number of publications, especially those after 2016. However, the search for the appropriate method that will provide the best combination between assessment tools and SDGs is underway. In the denim sector, there have been no previous studies on the combination of sustainability assessment tools and SDGs. Although there are indications that the findings obtained with LCA and MIPS support the SDGs in the present study, it is evident that a clear combination of the sustainability assessment tool and SDGs for the denim industry cannot yet be defined and needs to be developed.

4. Conclusions and Prospects

The main purpose of applying sustainability principles in the denim industry is to ensure economic efficiency and to keep the environmental impacts to a minimum. In this context, changes in the sustainable production potential of a factory producing denim fabrics were evaluated for 2017 and 2019. Accordingly, sustainability analyses were carried out both with LCA and MIPS methods based on the total production capacity, a selected product, and a wet process, and the contribution rates to the SDGs were calculated by associating the results with the UNEP 2030 SDGs. The results are presented below:

- It is recommended to use "total production capacity-based" data to evaluate the contribution to sustainability and SDGs in denim production.
- In the sustainability evaluation according to "total production capacity," it was determined that approximately 12% had been contributed to SDG 12 with both the LCA and MIPS approaches.
- Although there are inconsistencies in the LCA and MIPS results, it is predicted that there are economic and environmental gain potentials related to SDGs 13, 14, and 15, and the sustainable production potential of the factory can be increased in line with these targets.
- The targets that need to be worked on to increase the sustainable production potential in the denim sector were determined to be SDGs 9, 12, 13, 14, and 15.
- It is possible to say that cotton and electricity consumption are the most important sources of the environmental impact in the denim sector.
- The examined LCA and MIPS sustainability assessment methods did not generally yield consistent results within the scope of determining the contributions to UNEP 2030 SDGs in denim production. This shows that both methods alone produce results in a narrow framework, and there is a need for research and the development of integrated sustainability assessment methods for a more reliable and accurate sustainability assessment in a wider framework.
- It is thought that the findings will provide opportunities and focal points for the determination of cleaner production practices to be implemented in the factory in the future.
- It is thought that the study will guide the readers, researchers, and especially, denim manufacturers about associating the sustainable production potential with the SDGs. It is important to develop the work carried out in a single factory to apply it to the entire denim industry in the future and to create an integrated and standardized approach for the denim industry.

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Abbreviations

SDG	Sustainable development goal
LCA	Life Cycle Assessment
MIPS	Material Input per Service of Unit
UNEP	United Nations environment program
ISO	International organization for standardization
TS	Turkish standard
TS-EN-ISO	Quality management certification system
TS ISO	Quality Management system
CML	An impact assessment category
CML-IA	A database that contains characterization factors for life cycle impact assessment
ODP	Ozone layer depletion
MI	Material Input
MIT	Total material density
MIF	Mass density factor
MIC	Mass Intensity per Compartment
EU25	A Normalization method

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