Textile Science and Clothing Technology

Subramanian Senthilkannan Muthu *Editor*

Progress on Life Cycle Assessment in Textiles and Clothing

Springer

Textile Science and Clothing Technology

Series Editor

Subramanian Senthilkannan Muthu, SgT Group & API, Hong Kong, Kowloon, Hong Kong

This series aims to broadly cover all the aspects related to textiles science and technology and clothing science and technology. Below are the areas fall under the aims and scope of this series, but not limited to: Production and properties of various natural and synthetic fibres; Production and properties of different yarns, fabrics and apparels; Manufacturing aspects of textiles and clothing; Modelling and Simulation aspects related to textiles and clothing; Production and properties of Nonwovens; Evaluation/testing of various properties of textiles and clothing products; Supply chain management of textiles and clothing; Aspects related to Clothing Science such as comfort; Functional aspects and evaluation of textiles; Textile biomaterials and bioengineering; Nano, micro, smart, sport and intelligent textiles; Various aspects of industrial and technical applications of textiles and clothing; Apparel manufacturing and engineering; New developments and applications pertaining to textiles and clothing materials and their manufacturing methods; Textile design aspects; Sustainable fashion and textiles; Green Textiles and Eco-Fashion; Sustainability aspects of textiles and clothing; Environmental assessments of textiles and clothing supply chain; Green Composites; Sustainable Luxury and Sustainable Consumption; Waste Management in Textiles; Sustainability Standards and Green labels; Social and Economic Sustainability of Textiles and Clothing.

Subramanian Senthilkannan Muthu
Editor

Progress on Life Cycle Assessment in Textiles and Clothing

Springer

Editor
Subramanian Senthilkannan Muthu
Green Story Inc.
Toronto, ON, Canada

ISSN 2197-9863 ISSN 2197-9871 (electronic)
Textile Science and Clothing Technology
ISBN 978-981-19-9633-7 ISBN 978-981-19-9634-4 (eBook)
https://doi.org/10.1007/978-981-19-9634-4

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

This book is dedicated to
The lotus feet of my beloved Lord
Pazhaniandavar
My beloved late Father
My beloved Mother
My beloved Wife Karpagam and Daughters-
Anu and Karthika
My beloved Brother
Last but not least
To everyone working in making the textiles
and fashion sector SUSTAINABLE

Preface

LCA (Life Cycle Assessment) is the widely accepted method to assess the environmental impacts of a product in its different life cycle stages of a product from cradle to grave stages. ISO standards have earmarked 14040 and 14044 for life cycle assessment of products. LCA is widely used across various industrial sectors since many years. LCA is gaining its importance in textiles and fashion sector too in the recent years. I have been working on this field of LCA in textiles and fashion since 2008 and since my previous publications on LCA in textiles, including especially handbook of life cycle assessment on textiles and clothing which was published in 2016, there are many developments in terms of LCA in the textiles and fashion space. There are umpteen numbers of developments, I wish to record and publish these interesting LCA studies. I have received many interesting chapter proposals, and out of those, I have selected the best 11 chapters and compiled them in this book entitled, *Progress on Life Cycle Assessment in Textiles and Clothing*. Eleven eminent authors have authored these interesting chapters.

I take this opportunity to thank all the contributors for their earnest efforts to bring out this book successfully. I am sure readers of this book will find it very useful.

Toronto, Canada | Dr. Subramanian Senthilkannan Muthu

Contents

A Framework for Life Cycle Inventory Modeling of Chemical Substances in the Footwear and Apparel Industry 1
Nina van Dulmen, Puck Wammes, Nabil Ahmed, Pieter Witteveen, Laurent Vandepaer, and Jeroen Guinée

LCA Studies on Regenerative Agriculture and Regenerative Textiles: Two Routes of Regenerative Cotton 29
Rachit Kumar Sharma, Jagadeesh Nagireddi, and Subramanian Senthilkannan Muthu

Life Cycle Assessment of Textile Fibres in Brazil: A Literature Review 49
Juliana F. Picoli, Thais C. Guimarães, and Marina P. Colerato

The Role of Life Cycle Assessment in Analyzing Circular Economy Strategies in the Clothing Sector: A Review 83
Lorena Lizarzaburu-Egüez, Susana Toboso-Chavero, and Martí Rufí-Salís

Life Cycle Assessment of the Renting of Leisurewear 119
Felix M. Piontek and Martin Müller

The Role of Country-Specific Gate-to-Gate Ecolabels: Case Study for Sri Lankan Clothing Industry 129
V. M. Jayasooriya and L. Ranasinghe

Recent Progress on Life Cycle Sustainability Assessment in Textile Industry: Applications for Environmental, Economic, and Social Impacts of Cotton and Its Derivatives 163
Fatma Şener Fidan, Emel Kızılkaya Aydoğan, and Nigmet Uzal

The Environmental Impact of Textiles and Clothing: A Regional and a Country Approach 199
Marco Crestani, Laura Talens Peiró, and Susana Toboso Chavero

Performing Life Cycle Assessment at Scale in the Footwear Industry . . . 231
Michael Bär, Laurent Vandepaer, Vedanti Shah, and Stephan Pfister

Review of Microfibres from Various Industries and Its Life Cycle Burden on Environment 261
Nagireddi Jagadeesh and Baranidharan Sundaram

Life Cycle Assessment Approach to Denim Dyeing: Denim Dyeing with Natural Dyes 283
Selin Hanife Eryürük, Gülay Özcan, and Pelin Altay

About the Editor

Dr. Subramanian Senthilkannan Muthu is currently the Chief Sustainability Officer at Green Story Inc, Canada, based out of Hong Kong. He earned his Ph.D. from the Hong Kong Polytechnic University and is a renowned expert in the areas of Environmental Sustainability in Textiles and Clothing Supply Chain, Product Life Cycle Assessment (LCA) and Product Carbon Footprint Assessment (PCF) in various industrial sectors. He has five years of industrial experience in textile manufacturing, research and development and textile testing and over a decade of experience in life cycle assessment (LCA), carbon and ecological footprints assessment of various consumer products. He has published more than 100 research publications, written numerous book chapters and authored/edited over 100 books in the areas of Carbon Footprint, Recycling, Environmental Assessment and Environmental Sustainability.

A Framework for Life Cycle Inventory Modeling of Chemical Substances in the Footwear and Apparel Industry

Nina van Dulmen, Puck Wammes, Nabil Ahmed, Pieter Witteveen, Laurent Vandepaer, and Jeroen Guinée

Abstract The size and growth of the footwear and apparel (F&A) industry come with consequences. One of these is the environmental impact related to the life cycle of F&A: from extraction of resources to production, use, and disposal of the F&A products. Many actors in the industry aspire to perform a life cycle assessment (LCA), but due to supply chain complexity, companies may be prevented from doing so. Gathering data from further down the chain appears to be difficult, leading to data unavailability and incomplete LCA models. Currently, LCAs of F&A products include the production of all different components and their material inputs; however, there are several data gaps related to the production of chemical substances that are applied to F&A products. This is a significant limitation of current LCAs, as chemicals form a large part of the production of F&A products. Although data on chemical substance production appears to be difficult to collect from chemical suppliers, some data is available in the form of so-called safety data sheets (SDSs). In this chapter, a methodological framework is developed for compiling life cycle inventory (LCI) unit process datasets for the production and application of chemicals, where data gaps are filled using SDS. First, data gaps in current F&A chemical LCIs are identified, after which an assessment is performed to determine to what extent SDS can be used to fill these data gaps. Next, a framework is developed for using and extending data gathered from SDS to estimate unit process datasets for chemicals missing such datasets. Since not all information needed for an LCI unit process dataset is found in the SDS, the developed framework expands beyond the SDS as a source of information by also quantifying energy usage, transport, infrastructure, and chemical emissions related to a chemical substance, for a specific production activity. Finally, an illustrative example is provided of how the methodological framework

N. van Dulmen (✉) · P. Wammes · N. Ahmed · P. Witteveen · J. Guinée
Institute of Environmental Sciences (CML), Leiden University, Einsteinweg 2, 2333 CC Leiden, The Netherlands
e-mail: n.van.dulmen@umail.leidenuniv.nl

L. Vandepaer
On AG, Pfingstweidstrasse 106, 8005 Zürich, Switzerland
e-mail: laurent.vandepaer@on-running.com

S. S. Muthu (ed.), *Progress on Life Cycle Assessment in Textiles and Clothing*, Textile Science and Clothing Technology,
https://doi.org/10.1007/978-981-19-9634-4_1

can be used for the purposes of creating a more complete LCI dataset for the production and application processes of chemicals as part of the product life cycle of F&A products. From the study, it was concluded that a standalone SDS can be a source of information for approximately a quarter of the data needed for an example product reflecting the F&A industry. Thus, SDS cannot be the only source for building such unit process datasets. Applying the proposed framework allows for more complete datasets to be constructed.

Keywords Safety data sheet · Life cycle inventory · Life cycle assessment · Chemicals · Footwear and apparel industry · Methodological framework

Abbreviations

Cis	Chemical Ingredients
EFP	Energy flow parameter
EMF	Emission factor
F&A	Footwear and Apparel
HDEP	High-density polyethylene
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
SDS	Safety Data Sheet

Terminology

Chemicals	'Any basic substance that is used in or produced by a reaction involving changes to atoms or molecules' [6].
Substances	A specific set of chemicals for F&A products in the context of this research. Substances in F&A products can be cleaners, primers, hardeners, adhesives, and paints, and an SDS provides information about a certain substance; also referred to as a 'chemical substance'. Ingredients they are composed of are referred to as chemical ingredients. When not specifically referring to these five substances, chemicals are referred to as 'chemicals'.
Chemical ingredients (CIs)	Ingredients of which the substances of F&A products are composed.

1 Introduction

1.1 Chemicals Used for Footwear and Apparel Production

The footwear and apparel (F&A) industry is a fast-growing industry. This growth is caused by the growth of the global population, emerging economies increasing the purchasing power of their populations, and the continued growth of fast fashion [26]. The global footwear industry alone represented 365.5 bn US dollars in 2020 and is expected to be worth 530.3 bn US dollars in 2027, which is more than 20% of the global gross domestic product of the textile industry [29].

The size and increasing production of the F&A industry simultaneously come with their downsides. Demand is not only increasing because of the above-mentioned reasons, but also due to the shorter lifespan of F&A products. Remy et al. [23] state that such products are only kept by consumers for half of the time that they were 15 years ago. Most of these products are discarded unsustainably, which is not in line with, for example, the upcoming circular economy principles. In this economic model, value is created through multiple product life cycles, with minimal use of non-renewable energy and finite resources [16]. Throughout the life cycle of footwear, the processes of manufacturing, raw material extraction, and processing tend to be the most carbon-intensive and can account for over 70 percent of the life cycle emissions of the product according to Quantis [21]. Many of these embedded carbon emissions of the F&A industry originate from the significant amount of chemicals used in the production process [12]. As discussed by Hasanbeigi and Price [14], another environmental issue is related to the high levels of energy consumption required by the different production facilities throughout a product's supply chain. In the U.S., the textile industry accounted for around 2% of the total energy use of national manufacturing processes in 2010.

The current F&A industry is characterized by requiring large amounts of water, being energy-intensive, and using a wide variety of chemicals during production and processing [3]. The main environmental issues inherent in F&A production are characterized by emissions to water and air [10]. According to the European Integrated Pollution Prevention and Control Bureau (EIPPCB) [10], emissions to water during textile production are considered the most important, as water is used as the primary medium for applying dyes and finishing agents, as well as removing impurities. Additionally, textile production is estimated to be responsible for approximately 20% of global clean water pollution caused by the finishing and dyeing of products [9]. Lastly, Chequer et al. [8] estimated that approximately 8,000 different chemicals and 10,000 dyes are used in the F&A industry. Many of these chemicals are dangerous to human health and the environment and are regularly detected in F&A products [24]. Textile wastewater contains many of these toxic chemicals, which, if not treated properly, can cause serious damage to the environment and human health.

As many environmental issues can be identified for the F&A industry, it is of importance for the industry to understand and identify hotspots where changes could potentially be implemented to improve the environmental life cycle performance of an F&A product. To gain insights regarding the environmental impacts of their products, performing a life cycle assessment (LCA) is of great importance to companies operating in the F&A sector. However, according to Roos et al. [25], chemicals are generally inventoried in an incomplete way, and thereby the environmental impacts are improperly assessed within LCAs of F&A products.

Certain challenges can be identified that prevent companies from properly performing LCAs, mainly related to data unavailability due to a lack of information flows in the multi-tiered supply chain of F&A products. A large and complex network of contractors and suppliers operate in the F&A industry, all with their specific roles within the production process of a product. The different components of a product are produced by contractors and subcontractors, moving up the tiers of the supply chain until the assembly of the final product. Gathering data further down the chain is expected to be difficult, and so current LCA models often lack completeness regarding the modeling of chemicals used throughout processing and manufacturing. As a result, the corresponding embedded emissions and pollutants of F&A products are incomplete and probably underestimated. To improve this situation, a methodological framework is required for modeling the production and application of chemical substances, including their energy, water, transportation, packaging, and infrastructure requirements.

1.2 Safety Data Sheets and Modeling Challenge

Generally, safety data sheets (SDSs) are provided by suppliers throughout the supply chain of an F&A product as a source of information on chemical substances (referred to henceforth as substances). These sheets contain information about the chemicals used to create certain substances: their chemical ingredients (CIs), associated hazards (toxicological properties), and precautionary measures when coming into contact with them (see Fig. 2 for an example sheet). In the context of F&A, substances can be cleaners, primers, hardeners, adhesives, and paints, which are thus composed of combinations of certain chemicals. Henceforth, substances refer to these five categories of chemical substances, whereas CIs refer to the ingredients the substances are composed of. As the SDSs provide some data, they can be a source of information for the missing part in the existing life cycle inventories (LCI). However, according to Nicol et al. [19], SDSs often lack completeness and accuracy due to a lack of monitoring, incompatibility by the compilers, and poorly written characters. Currently, it is unclear what information can be of use, how the information can be quickly scanned and useful information found, and even whether the SDSs provide enough data to use for proper LCI development.

This study aims to identify how to use SDSs as a source of data as part of an LCI, while focusing on data for the production of substances used in F&A products. The study considers the extent to which SDSs can be used to model substances, to be able to develop complete and accurate LCIs for F&A production processes. First, the study identifies current data gaps that hinder the industry in its desire to conduct complete LCAs. Then, it considers to what extent SDSs can be used, and how remaining data gaps can be filled. Hereby, a methodological framework is developed that helps improve the modeling of substances throughout the supply chain, by drafting a working approach to model substances and filling data gaps. Lastly, the developed methodological framework is put into practice by applying it to a fictitious example product to show how the modeling is to be performed step by step.

The F&A industry will be able to use the framework to conduct more complete LCA studies themselves, by applying the methodological framework regarding chemicals to their existing or new LCA studies. Conducting more complete LCA studies help to identify the environmentally impactful CIs present in the product and enable the implementation of better alternative chemicals, raw materials, or technologies, while also serving as an input for future internal decision-making for improving the product and its process development. It is important to mention that while, for example purposes, the framework is applied to a footwear product in Sect. 3, it can generally be used for both footwear and apparel products.

Section 2 discusses the data needs for modeling substances for complete LCIs, presents how SDSs can be used to fill determined data gaps related to chemicals, and shows how remaining data gaps can be filled. Section 3 shows how LCA practitioners can use the framework presented in Sect. 2, by applying it to a sample case product. This section is followed by a discussion in Sect. 4, after which Sect. 5 presents concluding findings and recommendations.

2 Using SDSs for LCI Modeling: A Framework

As discussed in Sect. 1, the data estimation related to chemicals used for LCA purposes is a crucial part of determining the eventual impact of these chemicals for LCAs on F&A. This section discusses the data gaps for building LCIs of F&A products, what data can be found in SDS, and how these gaps can be filled with the help of SDSs. Lastly, it discusses how the remaining data gaps related to transport, energy use, and packaging can be filled.

The first important aspect is the substances used during product assembly. Data is required on the amounts of the substance used during assembly and the CIs it is composed of. It would be best if the production process of each substance is known, as this would provide specific data that can be used for LCI modeling, such as the energy needs and water consumption of these processes. Further, the type of CI should be known, i.e., organic or inorganic; this can help incorporate the infrastructural need for this type of chemical. Another aspect is the need for the transportation of substances to and from the suppliers, manufacturers, and the assembly plant. The distance between each facility and the required mode of transport provides an estimation of fuel use and therefore indirect emissions. Information on the packaging, such as the materials used in the packaging, and the maximum size of the packaging—in combination with the amounts of substance shipped—can identify indirect material use or waste flows

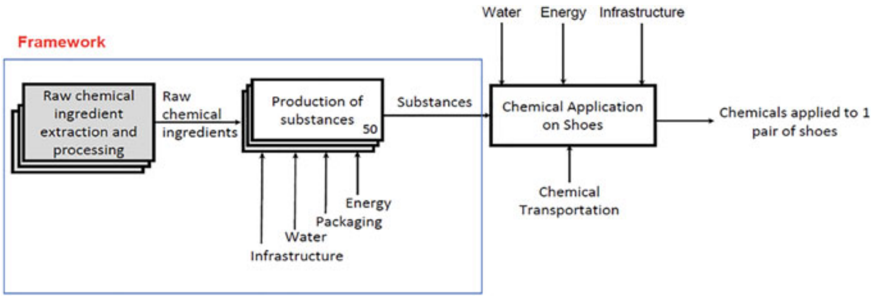


Fig. 1 Data needs for the production and application of chemicals (own image)

related to packaging. Figure 1 shows the data needs for the production and application of substances to an F&A product; here, a pair of shoes is taken as an example.

In short, to incorporate the impact of chemicals into an LCA, one needs information on the chemicals used to produce a given substance, its production process and infrastructure needs, packaging materials and transportation size, transportation distance and special needs, and lastly electricity, heat, and water used directly and indirectly in the production process. An overview of the required data for a complete LCI is shown in Table 1 under column 1 'LCI data required'. In addition, it is important to include the biosphere flows from the production of substances, such as emissions of chemical waste to air, water, and soil, in the system boundary of a product system.

As the aim of an LCA is to model the system as close as possible to reality, data gaps that are important for this assessment should be determined. The framework that is developed in this research, and which will be thoroughly addressed in this section, can be used as a general framework for companies in the F&A industry and, to some extent, other industries which use substances. Firstly, it is of importance to identify what data is available within a company (primary data) and can therefore be collected to identify further data needs. To discover to what extent SDSs can be used to fill in the determined data gaps related to chemicals, the following process can be followed.

To start with, the substances used for the production and manufacturing of the specific product that is under the interest of the LCA should be identified. For this product and the specific substances, the corresponding SDSs should be collected. As there is a specific SDS for each substance used for the production of the product, this includes a collection of several documents.

An SDS has a harmonized format and content created by The United Nations Globally Harmonized System (GHS) of Classification and Labeling of Chemicals [7, 20]. There are 16 sections in standard GHS safety data sheets, of which some are highlighted in Fig. 2. In addition to information about the supplier, the identification of the substance, its composition, and hazardous information, the SDS also includes information on measures regarding the first-aid, accidental release, and fire-fighting, as well as handling and storage, personal protection, toxicological and ecological

Section 1. Identification of the substance/preparation and of the company/undertaking

Product name: 1. Chemical name and type

Other means of identification:
Product code:
Recommended use of the chemical and restrictions on use

Intended use: Hardener

Identification of manufacturer, importer or distributor
Importer: 2. Adress

E-mail address of person responsible for Safety Data Sheet: [redacted]

Emergency information: [redacted]

Section 2. Hazards identification

GHS Classification:

Hazard Class	Hazard Category	Route of Exposure	Target organ
Flammable liquids	Category 2		
Acute toxicity	Category 4	Oral	
Serious eye damage/eye irritation	Category 2		
Specific target organ toxicity - single exposure	Category 3		Central Nervous System

GHS label elements:

Hazard pictogram:

Signal word: Danger

Section 3. Composition / information on ingredients

Substance or Mixture:
Mixture

Declaration of hazardous chemical:

Hazard component CAS-No.	Content	GHS Classification
3. Composition	4.Ingredient shares	Flammable liquids 2 H225 Serious eye damage/eye irritation 2A H319 Target Organ Systemic Toxicant - Single exposure 3 H336
		Acute toxicity 4; Ingestion H302
		Flammable liquids 3 H226 Acute toxicity 4; Inhalation H332 Skin corrosion/irritation 2 H315 Acute hazards to the aquatic environment 2 H401 Chronic hazards to the aquatic environment 2 H411

Fig. 2 Example SDS

Section 7. Handling and storage

Handling:	Take measures to prevent the build-up of electrostatic charges. Avoid open flames.
Storage:	Ensure good ventilation/extraction.Metal containers have to be grounded. Protect from direct sunlight. Temperatures between + 10 °C and + 40 °C

Section 14. Transport information

5. Packaging and transportation information

Road transport ADR:

Class:	3
Packing group:	II
Classification code:	F1
Hazard ident. number:	33
UN no.:	1173
Label:	3
Technical name:	[redacted]

Railroad transport RID:

Class:	3
Packing group:	II
Classification code:	F1
Hazard ident. number:	33
UN no.:	1173
Label:	3
Technical name:	[redacted]

Inland water transport ADN:

Class:	3
Packing group:	II
Classification code:	F1
Hazard ident. number:	
UN no.:	1173
Label:	3
Technical name:	[redacted]

Marine transport IMDG:

Class:	3
Packing group:	II
UN no.:	1173
Label:	3
EmS:	F-E ,S-D
Seawater pollutant:	-
Proper shipping name:	[redacted]

Fig. 2 (continued)

information, handling and storage, disposal consideration, physical and chemical properties, stability and reactivity, regulatory information, transport information, and any other information.

Within these sections, there are also regulations concerning what manufacturers do and do not have to include, meaning that certain data is available in one SDS but not in another. Therefore, there is a discrepancy in what can be found in SDSs. With this information in mind, the SDSs of the substances that are used in a specific product could be analyzed to provide insights into how much information is provided, which is also useful for LCI and information missing in SDS.

Table 1 List of data required for LCI and the availability in SDS

LCI data needed	Can be found in SDS
Chemical ingredients (CIs)	
Type	Yes
Percentage of mixture	Yes, the percentage ranges are given
Production process	Data unavailable
Infrastructure	
Type of chemical factory	Organic/inorganic, from the molecular formula
Quantity of chemical factory	Data unavailable
Transport	
Transportation type	Data unavailable
Transportation class	Yes
Distance from ingredient factory to substance factory	Data unavailable
Distance to the chemical factory from the Assembly factory	Can be derived from the address of site given in SDS
Packaging	
Group	Yes
Size	Data unavailable
Energy	
Heat consumption	Data unavailable
Electricity consumption	Data unavailable
Water	
Water consumption	Data unavailable

The SDSs of an example product are analyzed to show the percentage of LCI data availability. The analysis compares the required LCI data with data available in the SDS, as presented in Table 1. Figure 2 shows an example SDS, where the black boxes mask sensitive information and simultaneously show what information can be found where (e.g., the black box with number two masks the address line). The analysis of the SDSs shows that around 24% of the data points that are required for an LCI can be directly or indirectly found using an SDS. A sample size of 39 SDSs was analyzed for the availability of the 13 data points required, to understand how much of the data required could be found in an SDS. Points that lead to the same data entry were taken together to avoid overcounting the actual added value. Analyzing which data points are available in how many sheets provides an overview of total data needs and that here 24% can be acquired from SDSs.

2.1 The Use of Data Found in SDS

As mentioned in Table 1, an SDS provides a range of data. This section explains how this data can be used for LCI modeling of F&A products, thereby providing a critical analysis of the data quality.

Chemical ingredients

The SDS of a substance provides its chemical composition. However, this composition is given as percentage ranges and not as the exact composition of the substance. So, when using an SDS for modeling in LCA, the mean values need to be estimated to be able to model with a specific quantity. Modeling the chemical ingredient shares can be performed by adjusting the values that are given in the SDS, using the following example. Let us say that the SDS of Substance X lists that it is composed of three CIs, with their corresponding percentages: Ingredient 1 with 30–60%, Ingredient 2 with 10–30%, and Ingredient 3 with 10–30%. As these percentages do not add up to 100%, the average percentages are taken (45% for Ingredient 1, 20% for Ingredient 2, and 20% for Ingredient 3). Now, the percentages add up to 85%, which is why the remaining 15% should be filled by a proportional distribution of the surplus, based on the already available distributions, setting the final ingredient shares to 52, 24, and 24% for Ingredients 1, 2, and 3, respectively. It is now possible to calculate for each substance how much of each CI is used in its production. It should be mentioned that since the SDS can provide such wide percentual ranges, the actual shares of the ingredients can differ, but using these values will represent the average composition of Substance X. This does, however, remain a factor with high uncertainty, and these ranges should be used to perform uncertainty analyses.

Transportation distance

In general, transportation is required in the production process of substances and an F&A product. Firstly, from the factory where the CIs are produced to the factory where the substances (e.g., paints, hardeners, adhesives, etc.) are produced, and from the substance factory to the factory where the substances are finally used at the product assembly stage. The SDS does not have information about the location of tier 2 suppliers; hence, determining the transportation distance is not possible. However, as the CIs are modeled as background processes from databases such as Ecoinvent, it is recommended to use market activities which include the transportation flows. For the transport from the substance producing factory to the assembly factory, transport should be modeled manually. This can be done as, in most cases, the location of the supplying factory is provided in the SDS.

To find the required mode of transportation, online sources can be found showing an accurate estimation of the time required for transportation, mode of transportation—i.e., sea, truck, or train—and the kilometers that need to be traveled [27]. For the transportation from the substance factory to the assembly factory, the estimation can be relatively simple as the addresses of the substance producing factory are provided in the SDS, and the address of the assembly facility is generally known.

Other distances can be estimated and generalized, based on information about the substance producing country and the average distance between facilities there.

As an example, transportation between and through three typical locations of substance production factories and assembly facilities was modeled: Vietnam, Taiwan, and China. It was noticed that in most cases only a city and not a precise address could be used for the point of departure and point of arrival in online calculation sources. For the case of Taiwan, transportation data appeared to be difficult to estimate, whereas for the other countries, no issues were found. In this case, the online calculation source automatically took the center of the island of Taiwan as the point of departure and assumed the same main road is taken toward one of the main ports. It should be noted that the distances in general deviate slightly from the actual distances, due to the city-level location instead of address-level, and the transport from Taiwan or other islands may deviate even more. These discrepancies are considered to be appropriate for these initial estimations but could be submitted to a sensitivity analysis when a detailed LCA is conducted.

Transport type and packaging

Section 14 of an SDS (see number two in Fig. 2) includes information on transportation and packaging. Most SDSs contain information on packaging group, hazard class, and the UN number (United Nations Publications [30]. Some also state whether the substance needs special transportation equipment. Packaging material and size are important for the indirect material use estimation in the LCI.

A United Nations number (UN number) is a number composed of 4 digits as an identifier for hazardous products and materials for international transport [30]. These can be products such as toxic and flammable liquids, oxidizers, and explosives. UN numbers govern everything related to the packaging and transportation of materials in a global database. Certain information that they govern can be used in an LCA. This includes the kind of packaging that may be used to ship the material, the modes of transport that can be applied, how much material can be transported per container and per load, and the rules that apply to transporting the material via each different mode.

To continue, a hazard class is the indication of the properties of the goods transported. In order from 1 to 9, the classes represent the following: explosives, gasses, flammable liquids, flammable solids, oxidizing substances, toxic and infectious substances, radioactive substances, corrosives, and other substances. The packaging groups indicate the level of danger and are based on certain capabilities of these substances. For example, for Class 3 (flammable liquids), this packing group is assigned based on the degree of danger the goods present, based on the flash point and ignition temperature of the substance:

- Packing Group I: high danger, flash point: N/A, boiling point $\leq$35 °C.
- Packing Group II: medium danger, flash point $\leq$25 °C, boiling point >35 °C.
- Packing Group III: low danger, 25 °C$\leq$ flash point $\leq$65 °C, boiling point >35 °C.

In cases where the SDS does not provide information regarding the packing group, boiling and flashing points can be used to determine the packing group, according to the global standards for flammable liquid substances. Additionally, if none of this data is provided in the SDS, it can be assumed that the substance does not need special safety requirements.

Furthermore, the combination of the UN number, the packaging group, and the hazard class can lead to more information that can be found in the Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) book ([30], or online: see reference list). For example, UN 1133 with packaging group II leads to packaging instructions P001, R001, and IBC02, which can be found in the dangerous goods list. The P, R, IBC, and LP stand for the following:

- P: simple small packaging instructions for combination or single packaging.
- R: light-gauge metal packaging.
- IBC: intermediate bulk containers, which are larger, reusable, flexible, or rigid containers that are primarily used to transport liquid or viscous material.
- LP: large packaging.

All the UN numbers and corresponding dangerous goods lists can be found in the ADR book. The packaging instructions provide an idea of what materials are used for transportation and in which quantities. With this methodological framework, an indication of the materials used can be made, with the help of certain assumptions. These assumptions could be that the maximum quantity allowed to be transported within one container is used with, e.g., the most durable or cheapest material. The latter aspect can be part of a sensitivity analysis, including different possibilities and the effect this has on the system as a whole.

The more accurate source of information, however, would be consulting the UN number. As these codes are internationally recognized, they should be on packaged materials that are used throughout global trade. The UN Packaging codes provide packaging type identification codes, which include packaging type and material, packaging group level, phase of the item (solid/liquid), either gross mass or specific gravity, and hydraulic pressure, year, and country of manufacture. This code also includes the Pipeline and the Hazardous Materials Safety Administration (PHMSA) identification code. As the information on the packaging shows the actual packaging materials and size used, LCA results can be more accurate when using these numbers. However, due to supply chain complexity and its inherent underlying problems, it cannot be guaranteed that the codes are currently used in the country of production of the packaging, and are retrievable, or if they can be requested at the supplying facilities.

Lastly, as mentioned above, the SDS sometimes includes special transportation requirements, such as the type of truck with, for example, better ventilation capabilities. This can impact upon the amounts of fuel needed or other energy requirements. It was noted, however, that the majority of the F&A factories, assembly lines, and substance factories in a product's supply chain are located in countries in (South-East) Asia. These regions are known for their high temperate climates, and as all substances have different boiling and flash points that might be triggered in this climate, the packing group and mode of transportation are relevant to consider. Hence, it can be assumed that some of these substances require cooling transportation, depending on the average outside temperature and flash or ignition points at a certain time of the year.

2.2 How Can the Remaining Data Gaps Be Filled?

After consulting the SDS and retrieving all possible data, certain data points are still unavailable (see Table 1). In this section, an answer is offered as to how remaining data gaps can be filled, expanding beyond the use of SDS.

Chemical ingredients

To fill the remaining data gaps regarding the chemical ingredients (CIs), the framework presented in Fig. 3 can be used. This figure does not only include steps regarding filling data gaps, but also what the recommended approach is, in case the SDS does not provide sufficient information. The steps are as follows. Firstly, the SDS should be checked for CIs. If the CIs are mentioned in the SDS, the next step is to search for them in LCI databases such as Ecoinvent to find background data. If CIs are to be found in these databases, the ingredients and therefore the substance can be modeled. For this study, Ecoinvent is consulted as the primary LCI database. Even when the name of the CI is not mentioned in the SDS, in many cases the CAS number is. In this case, this CAS number can be used to find the chemical information. This number is a registration number developed by the Chemical Abstracts Service (CAS) and assigned to every substance [5]. Thus, by using online CAS number databases, all the information about this specific chemical can be found. Now, all the information needed to model the ingredient is available. In case there is no CAS number and no specific information about the ingredients, it is recommended to find a proxy chemical which has a similar production process or chemical properties by performing brief literature studies. In this situation, one can again look up the background information of this chemical proxy in Ecoinvent.

If a certain ingredient or its proxy is not available in Ecoinvent, one can consult other databases, such as the cm.chemicals database from Carbon Minds [4]. This database is specifically focused on the chemical industry. When an ingredient is found in an alternative database, one can continue modeling the CIs and substances. If the ingredient cannot be found in an alternative database, or when there is no proxy to be found in the literature, a generic CI from the Ecoinvent database can be chosen. In the Ecoinvent database, the chemical selected in this case is either ‘market for chemical, organic’ or ‘market for chemical, inorganic’. If it is not clear where the producing party is sourcing their separate ingredients, it is preferred to model with markets, as these already include transport (to the chemical production factory) and thus this does not have to be considered anymore. Due to data unavailability for the specific geographical regions, markets of a Global (GLO) and Rest-of-the-World (RoW) region are taken.

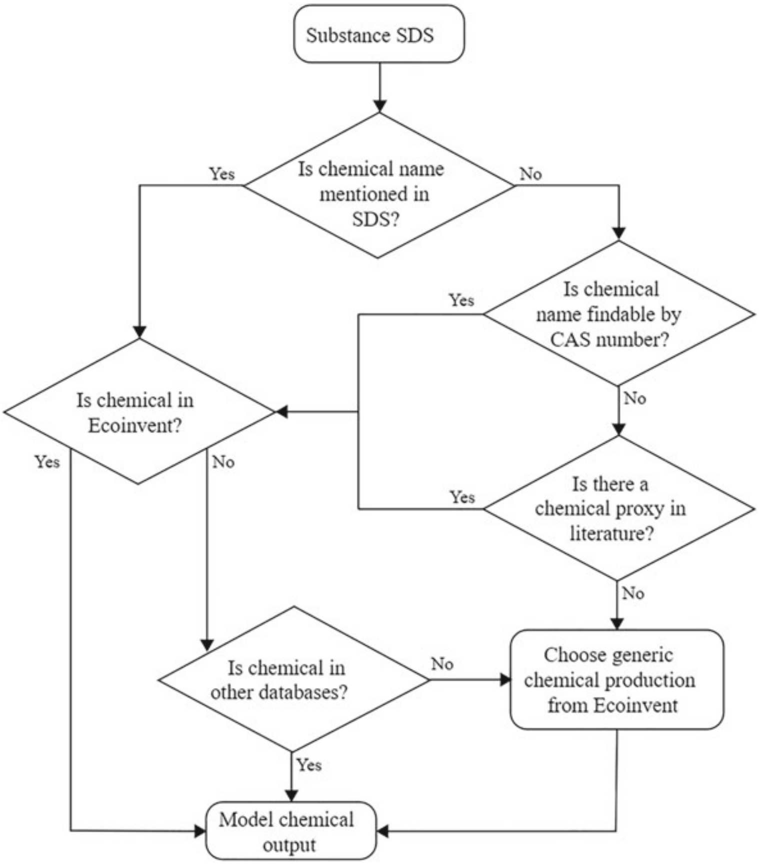


Fig. 3 The methodological framework for gathering data required for the modeling of the raw chemical ingredients for the substance production phase

Infrastructure

The building infrastructure of the producing factories also needs to be considered for a complete LCI. When there is no data available for the specific chemical factories where the substances are produced, a generic Ecoinvent infrastructure construction activity can be selected. For example, to model infrastructure, the activity 'chemical factory construction' with 'chemical factory' is used, with the value used for the production of chemicals to be 5.04e−05 kg. This proxy number is the average of the 'chemical factory construction' amount used in every process relevant to producing 1 kg of chemical output that can be found in the Ecoinvent database.

Water consumption

The use of water during the production of substances cannot be estimated using the SDS. For LCI development, it must be attempted to estimate the direct and indirect water consumption, if there is no further primary data available directly from the producing factories. Shafiei et al. [28] show that the average indirect water consumption in the chemical supply chains of China is 5058.73 m^3, and their direct water consumption is 2160.46 m^3 to produce 1000 m^3 of chemicals. For Taiwan, they concluded 76.57 and 580.18 m^3 for indirect and direct consumption of water, respectively. Shafiei et al. [28] show that water consumption can be estimated, however, they do not include all regions that are needed within the scope of all F&A products. Since there are already large differences in water consumption in these two example countries, the information is not generalizable and is therefore inconclusive. It is, however, a very important parameter and should be considered when data availability can facilitate this.

Energy consumption

Energy consumption is the use of energy (heat and electricity) during the process of the production of a substance. This information is not yet included in the Ecoinvent 3.9 background database. The energy required differs between substances; however, to offer an initial estimation, they can be divided according to substance category: pretreatment products (cleaners), primers, hardeners, adhesives, and paints. The energy consumption estimation is measured in MJ or kWh per kg of substance produced. It has been found that the different types of energy flows used in chemical factories are heat from natural gas (MJ/kg), heat from steam (MJ/kg), and electricity (kWh/kg).

An extensive literature review on energy used during the production of substances was performed and data aggregated from Ecoinvent was used (see Table 2). When multiple energy consumption values were found, the average value was used for the final energy consumption. When no values could be found in the literature, energy input values were found in the Ecoinvent database, using proxies or different kinds of the substance, as the five example proxies for cleaners in Table 2 show. It is important to highlight a distinction between different heat and electricity sources, as they cause different environmental impacts, which change the outcome of the LCA. In LCI databases such as Ecoinvent, there are several background processes available to incorporate the impact based on energy type, energy source, energy mix, country, and high and low voltage.

Emissions during the production of substances from CIs

It can be assumed that emissions occur, caused by the application of the CIs present in the substances specific to the respective F&A product. However, this topic is very difficult to elucidate, and not much research on this is available. Here, it is proposed to use emission factors (EMF) published in the supporting information from a study by Holmquist et al. [15]. Holmquist et al. [15] reviewed the scholarly literature on generic EMF and re-calculated them to enable them to be used in any basic scenario. Their study presents EMF to air, water, and soil (Table 3). These emission factors represent the fraction of the total quantity of chemicals used that is expected to be emitted to air, water, and soil, meaning that for each CI present in the substance, three corresponding emission flows are estimated.

Table 2 Energy flow parameters (EFP) according to substance type and accompanying calculations

Substance type	Energy type	Calculations/data findings in the literature					Average EFP	Source
Cleaners	Proxies (cleaners)	Methylcyclohexane production	Non-ionic surfactant production, ethylene oxide derivate	Methyl ethyl ketone production	Trichloroethylene production	Acetone production, from isopropanol		
	Heat from natural gas (MJ/kg)	21.527	2.15	2.15	2.15	2.15	6.02 MJ/kg	Ecoinvent
	Heat from industrial steam (MJ/kg)	12.015	0.2	0.2	0.2	0.2	2.5 MJ/kg	Ecoinvent
	Electricity (kWh/kg)	0.4709	0.416	0.416	0.416	0.416	0.427 kWh/kg	Ecoinvent
Primers	Electricity (kWh/kg)	Average of 135 and 185 kWh/ton = 0.16 kWh/kg					0.16 kWh/kg	Table 6.1 [2]
Hardeners	Heat from industrial steam (MJ/kg)						2.75 MJ/kg	Figure 3.1 [1]
Adhesives	Kinds of Adhesives	solvent-based adhesive (SBA)	Water-based adhesive (WBA)		Powder-based adhesive (PBA)			
	Electricity (kWh/kg)	1.40×10^{-2} kWh for 2.97×10^{-1} kg = 0.0471	1.38×10^{-2} kWh for 1.17×10^{-1} kg = 0.1179		2.35×10^{-1} for 3.56×10^{-2} kg = 6.6011		2.22 kWh/kg	Tables 3, 4 and 5 [17]

(continued)

Table 2 (continued)

Substance type	Energy type	Calculations/data findings in the literature		Average EFP	Source
Paints	Kinds of paints	Alkyd paint production, white, solvent-based, product in 60% solution	Alkyd paint production, white, water-based, product in 60% solution state		
	Heat from natural gas (MJ/kg)		5.62	5.62 MJ/kg	Ecoinvent
	Heat from industrial steam (MJ/kg)		3.14	3.14 MJ/kg	Ecoinvent
	Electricity (kWh/kg)	0.0713	0.167	0.119 kWh/kg	Ecoinvent

Table 3 Emission factors from Holmquist et al. [15]

Compartment	Value
Air	0.02
Water	0.01
Soil	0.009

The different emission factors are acquired as follows. In their literature study, Holmquist et al. [15] stated that chemical emission factors to air vary between 0.0000001 and 0.02, as a fraction of the total quantity of chemicals used. In some other cases, the air emission factors are based on volatility criteria or are applied across all chemicals. In the literature review performed by Holmquist et al. [15], a general factor of 0.02 for the emissions to air is derived by combining findings from this review, as described in the supplementary material of the study. Regarding the EMF to water, the literature study was more limited, as these are generally not adequately described [15]. Lastly, emissions to soil are rarely described [15], and for all chemicals, the same three emission factors should be used, whereas in reality, between the different chemicals, there can be slight differences in how much is emitted during production. As this study aimed to capture the average situation for emissions, the values found in Table 3 are averaged from the literature study they performed.

Overview of data points required

Table 4 summarizes the data points discussed in this section as an overview table. The different data points required are shown, along with data sources and descriptions to fill the data gaps. Here again, it should be noted that when on one aspect there is primary data available, it is preferred to use this as primary data is a more accurate source of information.

3 Application of the Framework on a Sample Case

This section puts the methodological framework as presented in Sect. 2 into practice. It discusses the general data needs for developing an LCI of an F&A product, taking a hypothetical pair of shoes as an example.[1] This example can be helpful when companies aim to conduct more complete LCA studies on their products and can be combined with company-specific data to build a complete and accurate LCI and thereby an accurate assessment of environmental impacts associated with an F&A product. This example is purely fictional and is only intended to be an illustration of how to apply the framework.

[1] The data generated in this chapter is purely fictional, taking the reader through the framework in a stepwise manner by using fictitious data. Therefore, it is not intended for any other use.

Table 4 The data sources and method applied for the estimation of data for each data point required

Data required	Data source/Method
Chemical substance production processes	
Chemical ingredient	Based on SDS or following methodological framework (Sects. 2.1 and 2.2)
Ingredient shares	Based on SDS
Energy	Literature review: average energy per substance type (Sect. 2.2)
Infrastructure	Use of generic process from Ecoinvent 'chemical factory construction' at 5.04e−05 kg (Sect. 2.2)
Transportation	Not required as background data from Ecoinvent are market activities
Packaging	Using company's primary data when sufficient, use UN numbers to make assumptions and perform sensitivity
Water	Primary data provided by the company, when available
Emissions	Using EMF (Sect. 2.2)
Chemical substance application process	
Amounts of substance applied	Primary data provided by the company, when available
Transportation	Based on the address of supplier in SDS and the address of assembly factory provided by primary data from the company
Energy, water, infrastructure, and direct emissions	Primary data provided by the company, when available. An issue can be that this data is aggregated for entire factory operations and not specific for chemical applications; it should be included in future aggregated assembly modeling

The presented five types of substances (cleaners, primers, hardeners, adhesives, and paints) are assumed to be necessary for the production and assembly of the shoes. The process for LCI data gathering for cleaners is described below, using the framework presented in Sect. 2. The same method is followed for the other substance categories.

Let us say that for the production of a given pair of shoes, Cleaner X is used, among others. The unit process table for the production of 1 kg of Cleaner X is required for constructing the LCI (see Table 5). The first step in creating this unit process table is to consult the SDS for Cleaner X (for an example SDS, see Fig. 2). An SDS for a substance provides information on the substance type, chemical ingredient data, hazard class, address of the production facility, and the substance packaging group and UN number.

The substance type presented in the SDS confirms this substance is indeed a cleaner, and the ingredient data tells us which ingredients the substance is composed

Table 5 Unit process table for Cleaner X

Process Type	Name	Reference product	Amount	Unit	Source
Output					
Substance	Cleaner X production	Cleaner X	1	kg	
Inputs					
Chemical ingredients	Market for ingredient 1	Ingredient 1	5.00e−02	Kg	SDS (composition)
	Market for ingredient 2	Ingredient 2	1.75 e−01	Kg	SDS (composition)
	Market for ingredient 3	Ingredient 3	7.75 e−01	kg	SDS (composition)
Transport			2.09e+02	tkm	SDS (site address)
Infrastructure	Chemical factory construction	chemical factory	5.04 e−05	kg	Table 4
Energy	Market for electricity, medium voltage	electricity, medium voltage	4.27 e−01	kWh	Table 2
	Market for heat, district, or industrial, natural gas	heat, district, or industrial, natural gas	6.02	MJ	Table 2
	Market for heat, from steam, in the chemical industry	heat, from steam, in the chemical industry	2.5	MJ	Table 2
Packaging	Steel drum/HDPE drum 140–200 L	14–18 kg/drum	9.50 e−01	kg	Manuilova [18]
Emissions					
Biosphere flows	Chemical emission (air)		3.50 e−03	kg	EMF
Biosphere flows	Chemical emission (surface water)		1.75 e−03	kg	EMF

of and in which proportions. In the product, Ingredient 1 has a 60–100 wt%, Ingredient 2 has a 10–30 wt%, and Ingredient 3 has a 1–10 wt%. By following the method presented in Sects. 2.1 and 2.2 regarding chemical ingredients, these numbers can be converted into the following ingredient shares:

- Ingredient 1: 77.5 wt%.
- Ingredient 2: 17.5 wt%.
- Ingredient 3: 5 wt%.

These values are then used to estimate the amount of ingredients in Cleaner X. After this, transportation, infrastructure, energy, water, packaging, and emission information needs to be added. Firstly, the SDS provides the address of the substance production facility, which is helpful for modeling transportation. Knowing both the address of the chemical factory and the assembly facility allows us to estimate the transportation distance for 1 kg of chemicals in ton*kilometer (tkm). Online sources are available for estimating freight transportation routes; for example, the international shipping, logistics, and freight route planner from SeaRates [27]. This tool shows the most logical transportation route, and which means of transport (train, truck, or ship) are generally used, and they can also provide a comparison between kilometers per transportation type, as explained in Sect. 2.1.

Infrastructure can be modeled using the value presented in Table 4. Energy flow parameters (Table 2) were used to calculate the energy requirements for Cleaner X. For the consumption of water, no data was available in the case of Cleaner X.

For packaging, additional primary data should be provided on the weight and type of the packaging container. For Cleaner X, this was given as follows: 14–20 kg/drum, but not the material that it was made of. The UN number and packaging group then confirm that this packaging is allowable with code IBC02, which refers to larger, reusable, flexible, or rigid containers, in this case, made from rigid plastics, metals, or composites. For rigid plastics, high-density polyethylene (HDPE) is most often used; while for metals, this stainless steel 304. As there is no Ecoinvent data on the IBC of these materials, this needs to be modeled in the foreground. Manuilova [18] has performed an LCA on industrial packaging materials of substances, including steel and HDPE drums. Even though the paper is relatively old, the industry for HDPE and steel has been relatively stable and, with minor adaptations, it is still believed to be valuable and usable to estimate emissions from the use of drums. However, the energy mix proposed has most likely changed since 2003,therefore, the sources of heat and electricity can be changed to the most current energy mix to be found in Ecoinvent. The functional unit in the study of Manuilova [18] is the packaging and distribution of 1000 L of a substance, which makes it directly adjustable to this example of 1 kg, by using the density of the CIs used. Moreover, Manuilova [18] describes three scenarios: optimistic, realistic, and pessimistic. With the optimistic scenario being 64% reused, 16% incinerated, and 20% to landfill. As steel and plastic recycling is becoming increasingly important and because it is relatively easy to do, it is assumed that the optimistic scenario is the current state and used in the case of Cleaner X (see Appendix 1).

The study of Manuilova [18] uses an average amount of 200 L per drum, based on the most often used drums. The estimated weight for 200 L is 21 kg, which is slightly above the weight given as primary data, however, depending on the thickness of the drum (with a minimum of 0.9 mm), this weight can vary. Since the weight variations of the drum are known, the volume can be deducted using the thickness, height, diameter, and density of the material of the drum. It is assumed that the estimations made by Manuilova [18] are applicable to this case for steel drums. As for HDPE drums, these are mostly around 8–10 kg for the same volume, meaning that in this LCI, either the volume of the drum is larger, or the material used is not HDPE. However, for the sake of the example, a drum size of 200 L is chosen. It is recommended to perform sensitivity analyses based on the packaging material type.

The last part that requires modeling are the emissions that are outputs from the production of Cleaner X. For this, the biosphere flows of Ingredients 1, 2, and 3 should be used. In the case of Cleaner X, only the biosphere flows of Ingredient 2 can be modeled, as the other flows do not exist in current LCI databases. Therefore, only the emissions from Ingredient 2 are modeled, with the note that in reality this is only a proportion of the total emissions coming from the production of Cleaner X. Table 5 shows the total unit process table for the modeling of Cleaner X.

4 Discussion

Companies in the F&A industry that aim to conduct complete and accurate LCAs for their products should take many aspects of different life cycle stages into consideration. The large and complex network of contractors and suppliers throughout the supply chain of a product makes data gathering at specific points in the chain difficult. LCA models, therefore, often lack completeness. The methodological framework presented in this study can support companies in achieving this objective, by providing guidance to improve the modeling of chemicals that are part of these F&A LCA studies. By following a framework using data from SDSs and filling the remaining data gaps, it is proven that an initial estimation of data points related to chemicals, which have been missing from LCIs of F&A products, can be determined. The ability to determine these data points is of value for quantifying more complete estimations of life cycle impacts of F&A products, as compared to the current status of LCAs, where chemicals are modeled with a proxy or simply ignored in the calculations. Of course, when primary data on chemicals is available within a company, it is preferable to use primary data as it will be more accurate.

Having followed this methodological framework step by step in Sect. 3, it has been shown that SDSs can be used for modeling chemicals for LCI datasets, but other data estimation techniques need to be applied in addition. An SDS only provides limited information, and the information it provides is not always of quality. SDSs provide data on the chemical ingredient shares and types, but the exact composition of the chemical ingredients is not provided. This means that the final impact of the different ingredients is still based on assumptions on the ingredient shares. In the above example (Sect. 3), it is modeled that Ingredient 1 has a share of 77.5 wt%, because of the range of 60–100% given in the SDS. Modeling this differently can lead to different outcomes in the LCA, and so this is a very uncertain factor, which should be investigated using uncertainty analyses.

An SDS only provides data on certain aspects, meaning it is only of limited value for LCI purposes. The largest factor that comes into play are trade secrets, and this means that certain more valuable and more accurate information cannot be presented, and other sources need to be consulted. For the other necessary data estimation techniques, generic data sources should be gathered, in the case of missing primary data. However, using this data leads to uncertainty margins of proxies, generic data, and non-region-specific data. As an example, the modeled emission factors are derived from a study that generalized these factors, thus an uncertainty analysis is recommended. Moreover, infrastructure is modeled generically, and precise transportation distances could not be calculated. Data gaps on transportation and packaging can be partially filled using SDSs. The distance from the substance producing factory to the product assembly facility is available from the address of the substance factory that is provided in the SDS, together with the location of the assembly facility which is generally known by the company. However, the exact distance from the chemical ingredient producing facility to the substance production location is only estimated using databases such as SeaRates. For special transportation needs and packaging instructions, the UN numbers provide information that can be acquired using, for example, the ADR handbook. However, this also leads to assumptions on, for example, the packaging size and materials. For both water and energy consumption, there is no data in the SDS on which assumptions can be based. Therefore, estimations have to be made concerning what the facilities in the country of production normally use during the production processes.

As several factors, such as CI composition, emission factors, and the modeling of infrastructure and transport, have been determined to be prone to uncertainty, it is recommended to perform Monte Carlo simulations and global sensitivity analyses (GSA). In LCA studies, the Monte Carlo analysis is used to measure the spread of uncertainty. This technique essentially entails performing numerous analyses with random input values selected from a predetermined probable range. The variability of the assessment's output can then be used to gauge the impact of this input uncertainty [22]. GSA is a variance-based sensitivity analysis, which can be used to find the contribution to output variance of each input parameter, the uncertainty distribution of output, and ranking parameters [13].

5 Conclusion and Recommendations

The key finding of this chapter is that the required information for the proper execution of a realistic LCA of F&A products, including chemicals, cannot easily be found in the SDSs provided by the suppliers operating in the supply chain of an F&A product. Different data estimation techniques need to be employed, complementing each other, in order to create more complete LCI datasets for the production and application processes of chemicals as part of the product life cycle of F&A products. The main question addressed in this chapter concerns how complete and accurate LCI datasets and LCA for footwear and apparel production processes can be developed using SDS to model chemicals. A methodological framework was developed that looks stepwise at (i) which data gaps can be identified in developing complete and accurate LCIs, (ii) to what extent SDS can fill these gaps, (iii) how the remaining gaps can be filled, and (iv) how this methodological framework can be applied to LCA models.

When incorporating the impact of chemical substances into an LCA of an F&A product, several data needs are apparent. The CIs used in the production of the substances, the production of these substances, and infrastructure needs should be considered. Moreover, other factors that require consideration include transportation, energy requirements, water usage, packaging, and emissions to air, water, and soil.

SDSs can be used as a source of information for modeling chemicals for LCI datasets. SDSs are composed following a harmonized section-based framework in which information valuable to LCI development is included. The data items readily available in SDSs are the chemical ingredient shares and types of a specific substance, which can be used to find appropriate background datasets from Ecoinvent. However, the exact composition of CIs is not provided, only a percentage range. This means that the final impact is still based on assumptions on the amount of ingredients used. For the CIs, everything related to the production process can be found in LCI databases (mostly Ecoinvent) using the proposed data gathering process (see Fig. 3).

Not all SDSs provide information with the same detail; meaning some SDSs provide more useful information than others. The largest factor that comes into play are trade secrets, and this means that certain more valuable and more accurate information cannot be presented. For data gathering and the generalizability of the methodological framework presented, it is important to have a degree of certainty regarding what information can be found and therefore used. An analysis of the 39 SDSs of an example product in terms of the availability of necessary LCI data points showed that approximately 24% of LCI data needs can be directly sourced from these sheets.

It became apparent that most of the information found in an SDS is incomplete, meaning that additional data gaps still need to be filled. Filling data gaps for transportation and packaging can partially be achieved with information found in the SDS. The address of the substance factory is readily available in the SDS, and together with the location of the assembly factory transportation distances and types can be estimated using services like SeaRates.

It was also found that data pertaining to the packaging type and thereby transport type can be derived from the UN numbers for chemicals. Hence, UN numbers should be collected from assembly factories, and the data collection can be automated by parsing the UN numbers and mapping them onto the corresponding information. For special transportation needs and packaging instructions, the UN numbers provide information that can be found using, for example, the ADR handbook. However, this also leads to assumptions on, for example, the packaging size and materials.

For both water and energy consumption, there is no data in the SDS on which assumptions can be based. No conclusive method for including water consumption when no primary data is available is identified. In the case of energy consumption, estimations can be made using emission factors following the presented methodological framework.

In conclusion, although some information can be found in the SDS (around 24% of total data needs), the SDS cannot be the sole source of information to fill the data gaps required to perform a full LCA on footwear and apparel. Additionally, there are remaining data gaps that need another solution. Ultimately, it is believed that this data gathering method can be useful in the initial stages of an LCA study; however, it would still be advisable to gain information from primary sources. For example, on transportation equipment used retrieved from UN packaging codes, or water consumption during production of both substances as their CIs received from the supplier. Adopting such an approach avoids the need for assumptions. It can prove beneficial for companies in the F&A industry to combine the chemical modeling with the rest of the assembly phase in their current LCA models and to quantify the overall impacts of production.

Due to the uncertainty, many factors are prone to conducting uncertainty analyses like Monte Carlo simulations and GSA is of great importance. It can be concluded that working with less uncertainty would be beneficial. Therefore, more specific data directly from suppliers would be beneficial in the accurate modeling and quantification of environmental impacts.

As the scope of the framework is only applicable to the production of substances, the process of the application of the substance during assembly of an F&A product is excluded, as is emissions leaching into the environment during the use phase, by for example washing the product. Future research should consider these aspects of the impact of chemicals in subsequent life cycle stages of F&A products.

Appendix 1. Unit Process Tables for the Optimistic Scenario Based on One Liter of Chemical Packed and Distributed, as Adapted from Manuilova [18]

Economic flows, out				
Amount steel drum	Amount HDPE drum	Unit		Product
1	1	liter of chemical transported in drum		Drum for transport
6.00e−03	6.00e−05	kg/liter		Slags and Ash
Economic flows, in				
Amount steel drum	Amount HDPE drum	Unit		Product
1.88	1.27	MJ/liter		Heat total
8.90e−03	1.43e−02	kWh/liter		Electricity total
4.25e−01	8.91e−01	kg/liter		Water
3.80e−02		kg/liter		Iron in ore
6.00e−03		kg/liter		Limestone
Environmental flows, out				
Amount steel drum	Amount HDPE drum	Flow name	Unit	Compartment
6.87e−01	1.86e−02	CO	g/liter	To air
5.17e+01	5.28e+01	CO_2	g/liter	To air
3.00e−03	9.82e−02	HC	g/liter	To air
2.40e−02	2.28e−01	CH_4	g/liter	To air

(continued)

(continued)

1.11e−01	2.02e−01	NOx	g/liter	To air
4.40e−02	4.76e−02	Particles	g/liter	To air
6.70e−02		SOx	g/liter	To air
	2.38e+01	SO_2	g/liter	To air
1.90e−02	7.24e−03	Cr	g/liter	To water
1.49		Fe	g/liter	To water
8.00e−03	3.47e−02	Suspended solids	g/liter	To water
	4.09e−03	COD	g/liter	To water
	8.47e−03	Dissolved solids	g/liter	To water
	2.53e−02	NO_3	g/liter	To water
	1.35e−02	SO_4	g/liter	To water

References

1. Althaus HJ, Chudacoff M, Hischier R, Jungbluth N, Osses M, Primas A (2007) Life cycle inventories of chemicals. Ecoinvent report, p 8
2. Bergek C (2011) Energy efficiency opportunities within the powder coating industry-energy audit and pinch analysis
3. Bhatia SC, Devraj S (2017) Pollution control in textile industry. WPI Publishing
4. Carbon Minds GmbH (n.d.) Cm.chemicals. LCA database for chemicals and plastics. https://www.carbon-minds.com/lca-database-for-chemicals-and-plastics/. Accessed 20 Aug 2022
5. CAS (2022) CAS registry. https://www.cas.org/cas-data/cas-registry. Accessed 21 Aug 2022
6. Cambridge University Press (2022) Cambridge dictionary. https://dictionary.cambridge.org/dictionary/english/chemical. Accessed 22 Aug 2022
7. ChemSafetyPro (2016) GHS safety data sheet http://www.chemsafetypro.com/Topics/GHS/GHS_safety_data_sheets.html. Accessed 2 Feb 2022
8. Chequer FD, De Oliveira GR, Ferraz EA, Cardoso JC, Zanoni MB, de Oliveira DP (2013) Textile dyes: dyeing process and environmental impact. Eco-Friendly Text Dye Finish 6(6):151–176
9. European Parliament (2020) The impact of textile production and waste on the environment [Infographic]. https://www.europarl.europa.eu/news/en/headlines/society/20201208STO93327/the-impact-of-textile-production-and-waste-on-the-environment-infographic
10. European IPPC Bureau (2019) Best available techniques (BAT) reference document for the textiles industry. https://eippcb.jrc.ec.europa.eu/sites/default/files/2020-01/TXT_bref_D1_1.pdf
11. faa (n.d.) Package for shipping. Faa. Gov. https://www.faa.gov/hazmat/safecargo/how_to_ship/package_for_shipping/. Accessed 4 Feb 2022
12. Green America (2017) Toxic textiles. The environmental and social impacts of our clothing. https://www.greenamerica.org/green-americas-2019-toxic-textile-report
13. Groen EA, Bokkers EAM, Heijungs R, de Boer IJM (2017) Methods for global sensitivity analysis in life cycle assessment. Int J Life Cycle Assess 22(7):1125–1137. https://doi.org/10.1007/s11367-016-1217-3
14. Hasanbeigi A, Price L (2015) A technical review of emerging technologies for energy and water efficiency and pollution reduction in the textile industry. J Clean Prod 95:30–44

15. Holmquist H, Roos S, Schellenberger S, Jönsson C, Peters G (2021) What difference can drop-in substitution actually make? A life cycle assessment of alternative water repellent chemicals. J Clean Prod 329:129661
16. Koszewska M (2018) Circular economy—challenges for the textile and clothing industry. Autex Res J 18(4):337–347
17. Maciel VG, Bockorny G, Domingues N, Scherer MB, Zortea RB, Seferin M (2017) Comparative life cycle assessment among three polyurethane adhesive technologies for the footwear industry. ACS Sustain Chem Eng 5(9):8464–8472
18. Manuilova A (2003) Life cycle assessment of industrial packaging for chemicals. Chalmers tekniska högskola
19. Nicol AM, Hurrell AC, Wahyuni D, McDowall W, Chu W (2008) Accuracy, comprehensibility, and use of material safety data sheets: a review. Am J Ind Med 51(11):861–876
20. OSHA (2012) Hazard communication standard: safety data sheets. DSG BR-3514
21. Quantis (2018) Measuring fashion: insights from the environmental impact of the global apparel and footwear industries study. https://quantis-intl.com/wp-content/uploads/2018/06/measuringfashion_globalimpactstudy_quantis_2018.pdf
22. Raynolds M, Checkel MD, Fraser RA (1999) Application of Monte Carlo analysis to life cycle assessment. SAE technical paper series
23. Remy N, Speelman E, Swartz S (2016) Style that's sustainable: a new fast-fashion formula. McKinsey & Company. https://www.mckinsey.com/business-functions/sustainability/our-insights/style-thats-sustainable-a-new-fast-fashion-formula. Accessed 9 May 2022
24. Roos S (2015) Towards sustainable use of chemicals in the textile industry: how life cycle assessment can contribute. Chalmers Tekniska Hogskola (Sweden)
25. Roos S, Jönsson C, Posner S, Arvidsson R, Svanström M (2019) An inventory framework for inclusion of textile chemicals in life cycle assessment. Int J Life Cycle Assess 24(5):838–847
26. Sadowski M, Yan C, Cummis C, Aden N (2019) Apparel and footwear sector: science-based targets guidance. https://sciencebasedtargets.org/resources/legacy/2019/06/SBT_App_Guide_final_0718.pdf
27. SeaRates (2022) International shipping, logistics & freight route planner. https://www.searates.com/route-planner/. Accessed 20 Aug 2022
28. Shafiei M, Moosavirad SH, Azimifard A, Biglari S (2020) Water consumption assessment in Asian chemical industries supply chains based on input–output analysis and one-way analysis of variance. Environ Sci Pollut Res 27(11):12242–12255
29. Statista (2021) Value of the global footwear market from 2020 until 2027. https://www.statista.com/statistics/976367/footwear-market-size-worldwide/. Accessed 4 Oct 2021
30. United Nations Publications (2016) European agreement concerning the international carriage of dangerous goods by road (ADR). Applicable as from 1 January 2017 (English ed.). United Nations. https://adrbook.com/en/2017/UN/1133

LCA Studies on Regenerative Agriculture and Regenerative Textiles: Two Routes of Regenerative Cotton

Rachit Kumar Sharma, Jagadeesh Nagireddi, and Subramanian Senthilkannan Muthu

Abstract In the current climate of concerns about global warming, the apparel and textile sectors are leading the way as the fastest-growing contributors of greenhouse gases (GHGs). Three different kinds of textile fibres include natural, man-made, and synthetic. Natural fibres come from plants and animals, while man-made fibres are manufactured from polymers generated from crude oil. Regenerative textiles are increasingly becoming popular with the aim to reduce the life cycle impacts of the textile products. Regenerative textiles can be obtained from the chemical recycling of the waste textiles, or by reusing and repairing the discarded textiles, and another way is through the use of regenerative agriculture techniques at the cultivation stage to enhance the overall environment friendliness of the textiles. Cotton is the fibre that is utilized the most in the textile industry, hence it is sometimes referred to as the "monarch" of the world's textile industries. The cultivation stage of cotton requires a significant amount of water for the plant's continued growth and is one of the most significant blue water consumers. Additionally, the production of cotton apparel results in the emission of high amounts of greenhouse gases, through its life cycle, which includes processes such as fibre ginning, yarn manufacturing, fabric production, colouring, printing, and the final assembly of clothing. Cotton production is undergoing a transition from conventional to organic and organic to recycled cotton. This change, which has been found to decrease some consequences on the environment, began with conventional cotton production. Because of recent advancements in the field of life cycle assessment (LCA), the analyst's job has become increasingly simpler, and estimating the environment impacts, using LCA tool, is now much less difficult. Recent research studies on cotton, aimed at identifying its environmental impacts, have led to various changes in the cultivation phase, which, in turn, have contributed to a lower consumption of traditional fertilizers. The newly discovered sustainable cotton fibre known as regenerative organic cotton was determined

R. K. Sharma · S. S. Muthu (✉)
Green Story Inc, Toronto, Canada
e-mail: drsskannanmuthu@gmail.com

J. Nagireddi
Department of Civil Engineering, National Institute of Technology Andhra Pradesh, Tadepalligudem 534101, India

S. S. Muthu (ed.), *Progress on Life Cycle Assessment in Textiles and Clothing*, Textile Science and Clothing Technology,
https://doi.org/10.1007/978-981-19-9634-4_2

to have less of an impact on the environment than either conventional or organic cotton. Although there are negligible studies found in the open literature, on cotton obtained through regenerative agricultural route at the moment, research in this field is becoming increasingly popular. The purpose of this chapter is to conduct a review of regenerative LCA studies and their future prospects.

Keywords Sustainability · Sustainable agriculture · LCA · Regenerative textiles · Regenerative agriculture · Cotton · Regenerative cotton · Regenerative agriculture practices

1 Introduction

Regenerative textiles are obtained from the waste textiles. This may include repairing and reusing [36] them or chemically recycling [40] them. The main aim of applying these strategies is to reduce the life cycle impacts of the textiles. Another way in which the environmental impact occurring through the life cycle of textiles can be reduced is by adopting the regenerative agriculture techniques. The natural textile fibres have traditionally been grown with conventional techniques of agriculture. However, recently organic farming techniques, wherein the use of natural fertilizers and pesticides is done, have gained quite attention. A further improvement to organic farming is regenerative agriculture, where a holistic approach is applied that takes care of the well-being of the earth, humans, and animals together.

The paper aims to conduct a review of regenerative LCA studies and its future prospects. This paper is structured as follows: We begin with an introduction in Sect. 1, followed by an introduction to LCA method in Sect. 2. Then Sect. 3 presents LCA studies in regenerative agriculture, which is followed by LCA studies in regenerative textiles, in Sect. 4. Next is the introduction to cotton fibre, which is presented in Sect. 5. In Sect. 6, possible routes of regenerative cotton are discussed. The next Sects. 7 and 8 briefly discuss the regenerative cotton fibres and present benefits of conducting life cycle assessment studies, respectively. Finally, Sect. 9 presents the conclusions and future scope.

The conventional agriculture, organic farming, and regenerative agriculture are compared in Table 1.

Table 1 Conventional, organic cotton and regenerative organic agriculture [20, 21, 30, 52]

Conventional agriculture	Organic farming	Regenerative agriculture
Depends on synthetic fertilizers, pesticides, and fungicides to boost food yields	Bans synthetic inputs, GMOs, antibiotics, and growth hormones	Encompasses organic farming and then raises the bar, prioritizing building soil health as a way to fight climate change
Often follows a factory model, with vast swathes of land producing single crops and animals raised in cages and feedlots	Instead, organic farmers use traditional techniques like composting, crop rotations, and grazing animals on pasture, drawing on centuries of knowledge	A holistic system, regenerative organic sees the well-being of earth, humans, and animals as interconnected. Some of the regenerative organic farming practices include crop cover, compost, crop rotation, intercropping, low-no-tilling, agroforestry, restorative grazing, and perennial crop
Big agriculture contributes a quarter of the world's total greenhouse gases, erodes top soils, generates toxic runoff, and damages health	Organic farming works with nature rather than against it	High standards for animal and worker welfare are critical

2 Life Cycle Assessment

Any product's production has both beneficial and adverse effects on the environment and subsequent generations. The comprehensive examination of these implications is referred to as the product's LCA. LCA is the inventory of all inputs and outputs for a product at all stages [25, 50, 57]. A building product, system, or entire structure can be used as the product. This review must be conducted at all stages of the product's life cycle, beginning with the creation or extraction of all raw materials and continuing through manufacturing, packaging, distribution, use, service life and maintenance, and end-of-life removal, disposal, recycling, or reuse of this product [34, 42, 46].

LCA is described as the collection and evaluation of a product system's inputs, outputs, and potential environmental consequences throughout its life cycle [49]. The illustration in Fig. 1 represents the life cycle system concept of natural resources and energy entering the system and goods, waste, and emissions exiting the system.

The LCA technique generates objective measures based on a quantitative inventory of all inputs and outputs connected with a product's or service's complete life cycle [22, 49]. This covers raw material extraction, product manufacturing, product distribution, and final product disposal [3, 26]. To assure reliable outcomes, LCA studies follow the approach outlined by International Organization for Standardization (ISO) standards. The ISO standards that are followed are as follows: ISO 14040: 2006-Environmental Management—Life Cycle Assessment—Principles and Framework [24], and ISO 14044:2006-Environmental management—Life cycle assessment—Requirements and guidelines, designed for the preparation of, conduct of,

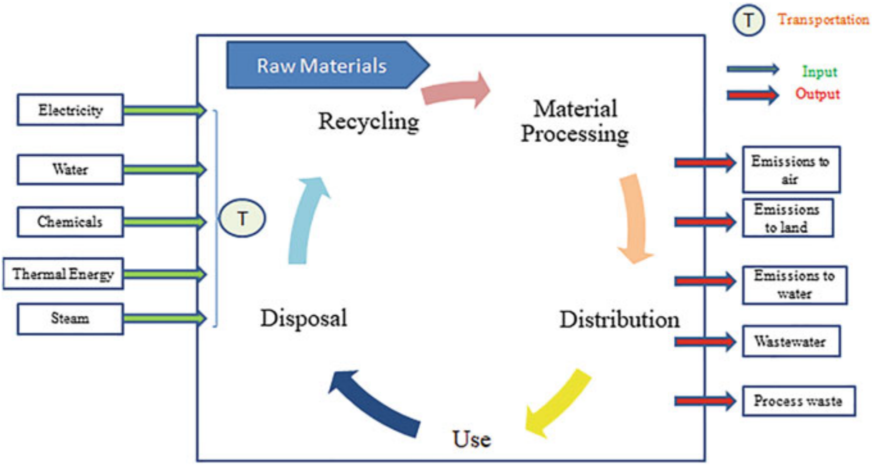


Fig. 1 Life cycle of a product

and critical review of, life cycle inventory analysis [18]. It also provides guidance on the impact assessment phase of LCA and on the interpretation of LCA results, as well as the nature and quality of the data collected.

In simple words, LCA is a tool which analyses everything that goes inside the system boundary such as raw materials, manufacturing of a product, operational/use phase, end of life, and disposal impacts on the environment [15, 25, 26, 31, 35, 61].

The main stages of LCA include goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and life cycle interpretation. These stages are presented in Fig. 2. The first stage “goal and scope definition” mainly includes expressing the production system in terms of system boundaries and functional unit. The second stage “life cycle inventory analysis” involves analysing the material flows, energy flows, and waste flows over the life cycle of a product. The LCI process quantifies the energy and raw material requirements, air emissions, wastewater quantities, solid wastes, and other releases for a product, process, or activity over its entire life cycle [49]. LCI is excellent for organizing product or process comparisons that take environmental aspects into account [7]. LCI Analysis involves compiling and quantification of a product’s inputs and outputs through its life cycle [7, 49]. In this stage, data is collected for each unit process, included in the system boundary, after which this data are utilized to quantify, inputs and outputs of the unit process. The collected data should be referenced to the functional unit, and the procedure of inventory analysis is an iterative one. The third stage “life cycle impact assessment” assesses the environmental impacts during the life cycle stages of a product. Life cycle interpretation occurs at each stage of the LCA process. Details of the stages in LCA process can be found in [23].

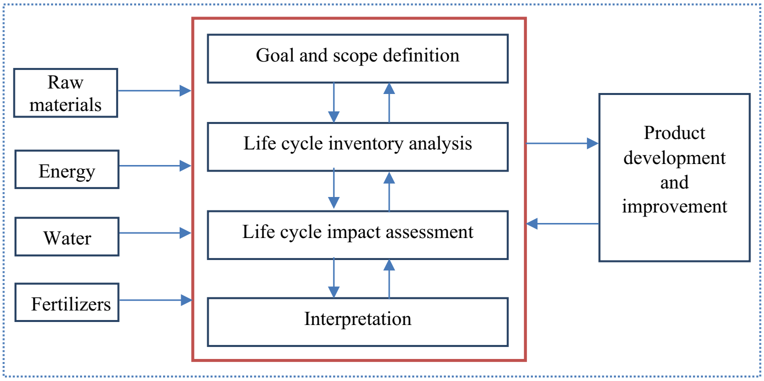


Fig. 2 Schematic diagram of life cycle assessment framework

3 Life Cycle Assessment Studies in Regenerative Agriculture

Regenerative agriculture is a farming principles system that restores the complete ecosystem and augments natural resources, rather than decreasing them [33]. It is a structure of farming practices and principles that boosts biodiversity, leads to soil enrichment and improvement in watersheds, and enhances ecosystem services [38]. Regenerative agriculture is the approach to farming that aims to restore soil health, and reversal of biodiversity loss [20]. Table 2 presents a summary of LCA studies conducted on regenerative agricultural farming.

4 Life Cycle Assessment Studies in Regenerative Textiles

Various authors in the past 16 years have utilized life cycle assessment to perform environmental sustainability assessments on regenerative textiles. LCA is the most established tool in the product associated assessment classification of tools utilized for sustainability assessment and has well developed datasets in varied areas [37]. Table 3 presents the summary of life cycle assessment studies done on regenerative textiles. There has been a growing effort from the industries to lower the environmental footprint occurring from their operations, and in this context, the studies have been conducted, for the purpose of making the processes more sustainable and finding their existing benefits.

Based on the summary of LCA studies on regenerative textiles, the list of fibres/materials on which LCA studies have been performed has been summarized in Table 4.

It can be observed from Table 3 that a greater number of life cycle assessment studies have been conducted on cotton fibre. In this context, the following sections

Table 2 LCA studies on regenerative agriculture

S. No	Author(s)	Title	Findings
1	Thorbecke and Dettling [64]	Carbon footprint evaluation of regenerative grazing at white oak pastures	The food product at WOP has a carbon footprint 111% lower than the conventional US beef system
2	Colley et al. [12]	Delta life cycle assessment of regenerative agriculture in a sheep farming system	Regenerative agriculture has the potential in improving the environmental performance of the sheep production in comparison with the prevalent industrial agricultural practices
3	Recanati et al. [50]	LCA towards sustainable agriculture: The case study of cupuaçu jam from agroforestry	Preliminary results showed up the gains of producing jam from fruits harvested in an area of the Amazon that had been reforested via agroforestry, and also the high variability of environmental impacts due to the differences in the alternative agricultural systems considered
4	Rowntree et al. [54]	Ecosystem impacts and productive capacity of a multi-species pastured livestock system	The study conducted a whole farm LCA of multi-species pasture rotation of a farm converted from degraded cropland. Results indicate MSPRs are a useful model for alternative livestock production systems with improved environmental outcomes
5	Caputo et al. [10]	Energy-environmental assessment of the UIA-Open Agri case study as urban regeneration project through agriculture	The impacts linked to the practices executed (organic agriculture, including agroforestry, intercropping, and ancient grains) lessen by an average of 55% in energy utilizations and 65% on GWP if compared with conventional ones

Table 3 LCA studies on regenerative textiles

S. No	Author(s)	Title/Purpose	Findings
1	G. Peters et al. [45]	LCA on recycling of blended fiber fabrics	The recycling system competed good with single use alternatives for a small majority of indicators. While it performs less with respect to energy consumption, green gas emissions, and acidification, the outcomes are of the same order of size as the single use alternatives
2	G. Peters et al. [44]	LCA on fast and slow garment prototypes	The results suggested that the environmental outcomes of the paper-based garments could be competitive with reference garment, specifically when the user is presumed to discard a fully usable reference garment after five uses The principal factor aiding the paper-based garments is the pruning in the impacts per mass linked with material manufacture (spinning, knitting, fibres), and also their lighter masses
3	Rosson and Byrne [53]	Comparative gate-to-gate life cycle assessment for the alkali and acid pre-treatment step in the chemical recycling of **Waste cotton**	Sulphuric acid approach has a considerably lesser impact compared to the sodium hydroxide approach and hence is chosen as the favoured technique for making regenerated cellulose fibres from textile waste
4	Turrillas and Guardia [65]	Environmental impact of **Recover cotton** in textile industry	The use of the recovered cotton to produce the high quality provides an added value to the products from an environmental point of view

(continued)

focus on cotton fibres and provide an introduction to cotton fibre, regenerative cotton fibre, and possible routes of regenerative cotton.

Table 3 (continued)

S. No	Author(s)	Title/Purpose	Findings
5	Bodin [8]	A case study of the environmental impacts of two alternative waste management strategies for household textile waste in nine municipalities in northern Stockholm, Sweden	The reuse scenario is preferable to incineration scenario, since the avoided production phase was a major contributor to environmental impacts
6	Farrant et al. [16]	Environmental benefits from reusing clothes	Cloth reuse can greatly help in reducing the environmental burden of clothing
7	Pegoretti et al. [41]	Use of recycled natural fibres in industrial products: A comparative LCA case study on acoustic components in the Brazilian automotive sector	**DL-cotton** combining two layers of recycled fibres of different densities is the best alternative from an environmental perspective
8	Shen et al. [59]	Open-loop recycling: A LCA case study of PET bottle-to-fibre recycling	Chemical recycling produces recycled fibres and helps to lessen the impacts in 6 to 7 categories out of a total of 9 categories when compared to virgin PET fibres
9	Woolridge et al. [66]	Life cycle assessment for reuse/recycling of donated waste textiles compared to use of virgin material: An UK energy saving perspective	For every kilogram of virgin **cotton** replaced by second-hand clothing, there is an approximate saving of 65 kWh, and for every kilogram of polyester, this saving is around 90 kWh. Reuse and recycling of the donated clothing lead to a lessening of the environmental impacts when compared to purchasing new clothes
10	Babel et al. [5]	Comparative Life Cycle Assessment (LCA) of second-hand vs new clothing	Second-hand clothing has major ecological savings compared to new clothing across 3 environmental impact categories considered in the study

(continued)

Table 3 (continued)

S. No	Author(s)	Title/Purpose	Findings
11	Angelstam et al. [2]	Comparative LCA Viscose vs **Cotton** T-shirts	The results of the study exhibit that a viscose T-shirt has a superior environmental showing than one created from cotton
12	G. M. Peters et al. [43]	Environmental Prospects for Mixed Textile Recycling in Sweden	A completely unified viscose production system or a system that creates one of the newer cellulosic fibres from the **recovered cotton** will enhance the environmental performance of the recycling system compared to its alternatives
13	Straten et al. [62]	A life cycle assessment of reprocessing face masks during the Covid-19 pandemic	Reuse and reprocessing of disposable face masks for 5 times exhibits a lesser climate change impact and lower costs
14	Fidan et al. [17]	An integrated life cycle assessment approach for denim fabric production using **recycled cotton fibers** and combined heat and power plant	The use of **mechanically recycled cotton** and a CHP plant as an energy source during the denim production manufacturing process aids the shift from conventional linear economy business models of companies to a circular economy
15	LCA of Recycling Cotton [29]	LCA of recycling **cotton**	The results strengthen the case for recycling
16	Nellström and Saric [36]	A Comparative Life Cycle Assessment of Nudie Jeans' Repair and Reuse Concept	The results show that the environmental impacts lessen by increasing the lifetime of the jeans
17	Spathas [60]	The Environmental Performance of High Value Recycling for the Fashion Industry LCA for four case studies	In the two systems involving mechanical recycling and high recycled input percentage, the recycled yarns had lesser impacts compared to virgin products in all impact categories. This was assigned to replacing the virgin cotton production and virgin PET input, for the favour of recycled ones

(continued)

Table 3 (continued)

S. No	Author(s)	Title/Purpose	Findings
18	Schmidt et al. [57]	Gaining benefits from discarded textiles LCA of different treatment pathways	**Cotton** gives great environmental benefits per tonne, specifically for reuse scenarios

Table 4 List of fibres and materials on which LCA studies have been performed

S. No	Fibre/Materials
1	Recycled wool
2	Fibres blends like polycotton (a mix of polyester and cotton)
3	Waste cotton
4	Recovered cotton
5	Household textile waste
6	Dual-layer polyurethane (DL-PU) panel, recycled textile absorption-barrier-absorption (ABA-cotton) panel, and recycled textile DL (DL-cotton) panel
7	PET bottle-to-fibre
8	Donated waste textiles
9	Second-hand versus new clothing
10	Viscose versus cotton
11	Mixed textile recycling
12	Face masks
13	Recycled cotton fibres
14	Discarded textiles

5 Introduction to Cotton Fibre

All the way from raw material procurement (fibres) through semi-processed (yarns, woven, and knitted fabrics with their finishing process) to finished consumer goods, the textile and apparel industry encompasses a vast array of specialized industries. Textile fibres may be broken down into two broad groups: natural and man-made. All-natural fibres are harvested from plants or animals. Man-made fibres accounted for around 60.1% and natural fibres for approximately 39.9% of worldwide textile fibre consumption in 2010. More than 82% of all natural fibres used annually are cotton, making it by far the most popular and frequently used fibre on the planet [6]. Cotton accounts for the vast majority of all natural fibres sold in the textile industry. This includes silk, wool, flax, hemp, etc. However, there are challenges connected with its production, such as the fact that it can only be grown in sub-tropical temperatures and requires a lot of water and the use of agrochemicals to provide satisfactory results [28]. The majority of published cotton LCAs concentrated on the primary producers across the world (India, China, and the United States) [4]. In terms of textiles, waste

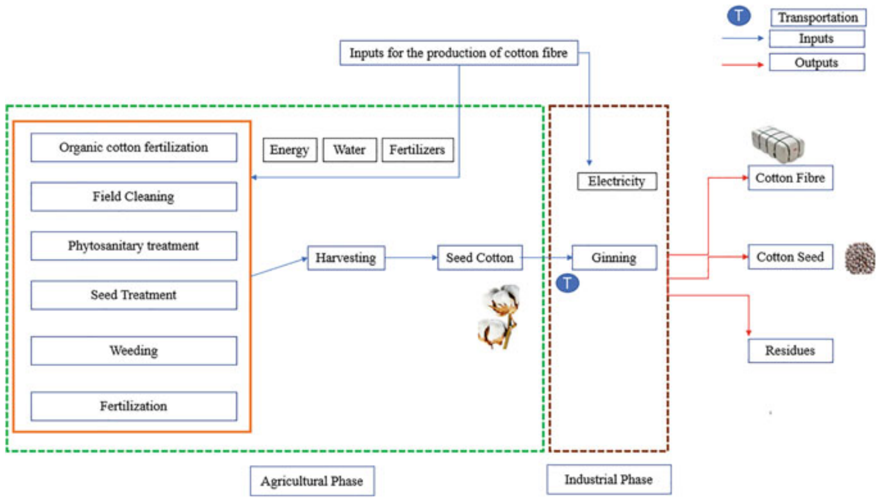


Fig. 3 The general production process of cotton fibre

jeans, also known as waste denim fabric, make up the great majority. These jeans are composed of cotton and polyester fabric with variable weight ratios, nevertheless, the vast majority of denim is still produced from pure virgin cotton that is coated with textile colours [70]. The general production process of cotton fibre is presented in Fig. 3.

6 Possible Routes of Regenerative Cotton

There are two main routes through which regenerative cotton can be produced. These are presented in Fig. 4. The first route is the recover recycled route, which is the cotton that has been regenerated through mechanical and chemical recycling techniques. A literature search reveals a limited number of LCA studies. The second route is the regenerative agriculture route, which is the cotton fibre that has been obtained through regenerative agriculture techniques. Open literature search reveals negligible LCA studies.

6.1 Cotton-"Recover/Recycle Route" LCA Studies

This section provides expanded details of the LCA studies on regenerative cotton obtained through the recover/recycle route. Table 5 gives a summary of LCA studies conducted on cotton obtained through the recover/recycle route.

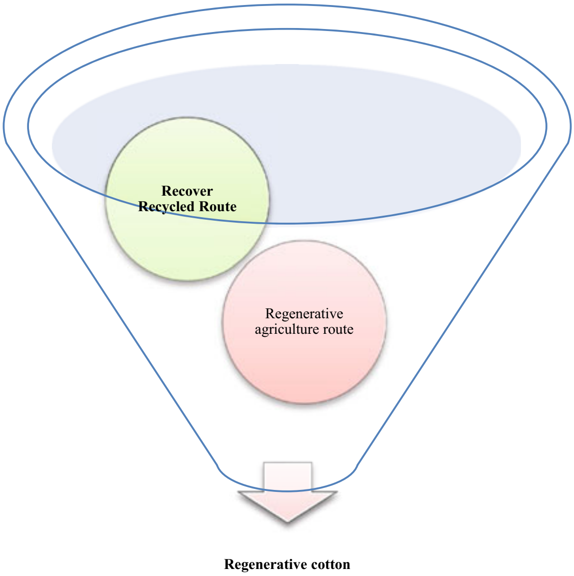


Fig. 4 Two routes of regenerative cotton

6.2 Cotton-"Regenerative Agriculture Route" LCA Studies

Literature search reveals that there are negligible studies available on the life cycle assessment of regenerative cotton obtained through the regenerative agriculture route in the open literature. However, literature is abundant with the description of the various techniques that are followed in regenerative agriculture. Performing a life cycle assessment on regenerative cotton obtained through the regenerative agriculture route would require an understanding of these techniques, employed during the cultivation of crops. Varied sustainability techniques are employed in regenerative agriculture. All these techniques are focused on making agriculture more sustainable and environment friendly. This section presents major techniques that are followed in regenerative agriculture.

- *No tilling of land*

No-tillage or no-till, additionally called zero tillage, is a soil cultivation system wherein seeds are deposited right into untilled soil. It is defined "as a system of planting (seeding) plants into untilled soil through opening a slender slot trench or band of enough width and intensity to achieve right seed coverage. No extra soil tillage is done. No-till farming is not just limited to soil tillage, but it also includes four main, convoluted management practices, which are minimum soil interference (no harrowing and ploughing), maintaining a constant vegetative soil cover, direct sowing, and sound crop rotation [19]. No-tillage is a differentiated soil control system that seeks to decrease the effect of agricultural activities. Under this method, plant residues from preceding vegetation are left at the soil surface, ensuring insurance

Table 5 Expanded details of the LCA studies conducted on cotton obtained through the recover/recycle route

S. No	Author	Goal	Functional unit	System boundary	Year
1	G. M. Peters et al. [43]	Environmental prospects for mixed textile recycling in Sweden	"Recycling of 850 tonnes of mixed textile waste"	Cradle-to-gate	2019
2	Nellström and Saric [36]	A comparative life cycle assessment of nudie jeans' repair and reuse concept	"One pair of Nudie Jeans used for one year"	Cradle-to-grave	2019
3	Schmidt et al. [57]	Gaining benefits from discarded textiles LCA of different treatment pathways	"Treatment of one tonne of used textiles discarded by households and organizations, from the point of collection until its final grave"	PEF framework aims at assessing the cradle-to-grave impacts	2016
4	G. Peters et al. [45]	"To find out to what extent the BRW recycling process developed in the Mistra Future Fashion program can provide benefits over business as usual"	"The production of fibres equivalent to the potential production from Sweden's annual commercial laundry waste flow, i.e., 350 tonnes of polyester and 280 tonnes of regenerated cellulose fibres"	Cradle-to-gate	2019
5	Rosson and Byrne [53]	"To assess the difference in environmental impacts caused by two methods for lowering the Degree of Polymerization (DP) of cotton waste"	"Pre-treatment of 10 g cotton waste"	Gate-to-gate	2020

and safety from erosion processes. Furthermore, the soil is only manipulated at the moment of planting, while a groove is opened in the soil so as to deposit seeds and fertilizers [63]. Among the advantages of these methods, are discounts in manufacturing prices and environmental impacts, advanced water retention and infiltration in the soil, reduction of abrasion and nutrient loss through wind action, discount in the threat of river siltation, upgrades in soil potential to hold natural substances for longer periods, decrease in soil compaction, decreased fuel intake through mechanical implements, trimming of required agricultural operations, cut in climatic risks that can have an effect on manufacturing and harvest, upgrades in water-use efficiency, upgrades in soil buffer potential, enhancement in natural content material of soils, enhancement in worm and microorganism populations, enhancement in reserves of N, P, and K in soils, diminution in the toxicity of Al, Mn, Cd, and pesticides, the opportunity of extra opportune planting times, and allowance of greater time for different farm activities [63]. Furthermore, no-tillage includes lower prices of manufacturing, contributes to carbon sequestration, and calls for much less use of tractors [63]. Conservation tillage has the capability to result in improved soil situation and crop yield with minimum effect at the surroundings [9].

- *Cover crops*

According to Soil Science Society of America (SSSA), cover vegetations are the ones used to defend and enhance the soil between instances of normal annual crop production or among trees in orchards and vines in vineyards [27]. Through the right management, cover crops can be applied as an critical element of soil conservation practices for superior soil health [27].

- *Rotation of crops*

Crop rotation is powerful in mitigating weed, insect, and pathogen strains because of the enhanced richness of residual roots and litter in cropping soils which can also additionally enhance crop yields [68]. Crop rotation practices improve soil organic matter input derived from numerous crop residues and for that reason enhance soil quality and structural stability [68]. For instance, soil organic carbon (SOC) and pH are better in crop rotation compared to mono-cropping systems [68].

- *Biological pesticides like neem oil*

The use of chemical pesticides has performed a main function in growing agricultural production and additionally in shielding plants from damage resulting from insect pests. However, it was estimated that almost 0.1% of the agrochemicals used to guard plants reach goal pests while 99.9% persist in environment, human beings, and domestic animals and reach water resources [48]. Botanical pesticides are environmentally beneficial alternative methods to shield crops. The assessment of plant extracts for their deadly consequences on insect pests is one of the techniques used to look for new insecticides [48]. Rashwan and Hammad [48] aimed to assess the toxicity of algal species, spirulina platen-sis (blue-green micro alga) and sargassaum vulgar (brown marine macro alga) as natural pesticides in opposition to cotton leaf worm spodoptera littoralis (lepidoptera: noctuidae). Plants like azadirachta indica (Neem) and vitex negundo (nochchi) were effectively used as sources of secure insect sprays for the removal of worm and jungle fever vectors separately [56]. Botanical pesticides are effective in handling distinctive crop pests, inexpensive, effortlessly biodegraded, and have numerous modes of action,their sources are effortlessly available and feature low toxicity to non-target organisms [56].

- *Intercropping*

Intercropping is the technique of cultivation of more than one crop in the same field at identical times to increase crops interaction [35]. Intercropping cultivation systems are successful initiatives to boost crop production by way of improved use of farmlands and little resources [69]. Intercropping ameliorates sustainable production particularly under continuous cropping systems by amplifying the biodiversity of agroecosystems. More resource use efficiency is obtained in intercropping component crops that have a big divergence in growth time spans and a profound requirement for nutrients that take place at different times [35].

- *Efficient use of irrigation water*

Irrigation method has a huge impact on water utilization, productivity, and profitability of particular crops. Drip irrigation increases unit productivity of water as well as land, helps in administering fertilizers efficiently, leads to increased and efficient distribution of nutrients, much less plant stress, early harvests, reduction in yield wastes, improved crop condition, and elevated yield homogeneity [32]. Drip irrigation improves land suitability by 38% in comparison to surface irrigation. Drip irrigation system reduces the price of production constituents such as labour, fertilization, and cultivation,however, the initial cost for setting up the system is high as compared to the surface irrigation system [32]. Latest irrigation techniques which include sprinkle irrigation, drip irrigation, and infiltrating irrigation can reap better IWUE and appreciably lessen water use by 30–100% in comparison to standard surface irrigation [67]. The change from flood to drip irrigation lessens the recharge fraction (19% vs. 16%) also particularly the nitrogen leaching fraction (33% vs. 18%) on the long term [47].

- *Adjusting the densities of plants and panting dates*

The rate of nitrogen application and plant density are important elements that sway cotton production significantly. The plant populace is one more critical point affecting cotton yield and its related characteristics [39]. Optimal plant density varies from environment to environment. Dense populations comprise overgrown shades of plants, that cause fruit degeneration, fruit absorption, rise in plant height, and deferred maturation, leading to diminished yield and quality of fibre [39]. Excessive plant density intensifies interplant rivalry for water, nutrients, and sunlight, which is likely to cause abiotic stresses that impact plant growth, plant architecture, and plant development patterns, plus the carbohydrate production and its distribution [71]. Local conditions must be considered while determining the optimum plant density and planting dates, in order to achieve maximum grain yields [14]. However, these techniques need to be analysed for their positive impact on the supply chain impacts reduction using LCA.

7 Regenerative Cotton Fibres

Regenerative Organic Certification Cotton is concerned with the preservation of the environment, the nurturing of the world, and agricultural practices that are fair than organic cotton [51]. It qualifies for the most stringent regulations for organic farming.

The cotton is grown without making use of any artificial components, such as hormones or antibiotics. Alongside the main crops, cover crops [27, 35] are often planted that help increase the amount of organic matter in the soil, store carbon, and lessen erosion. Compost is a kind of organic fertilizer and pesticide that is created by farmers out of waste products from agricultural production [1]. Crop rotation refers to the practice of moving crops in a regular way from one year to the next [11, 13, 58]. Intercropping [35] and no tilling [63] are other practices that are involved.

8 Major Benefits of Conducting Life Cycle Assessment Studies

LCA results can be used to provide conclusions and recommendations that are mainly focused on possible improvements in the materials, processes/manufacturing, and distribution. Results can be helpful to improve the existing supply chain configurations with better technologies, improved processes, etc. Analysis can be used to highlight the contribution as a percentage, of each individual processes in the overall environmental impacts, through the life cycle of a product. If the company is already implementing a green practice in its supply chain, it can use the results to identify how much environment impact they are able to lessen by following that practice.

9 Conclusions and Future Scope

This chapter aimed to develop an understanding of the life cycle assessment of regenerative cotton. The purpose of this chapter was to conduct a review of regenerative LCA studies and its future prospects. A literature search has been conducted which indicated that a limited number of LCA studies on regenerative textiles exist in the literature. It was observed that there are negligible LCA studies in the open literature on cotton obtained through the regenerative agriculture route. The review has been able to build a background to carry out a life cycle assessment of cotton obtained through regenerative agriculture. Other main conclusions drawn from the review are summarized as follows:

- Performing LCA studies helps to identify the specific areas of improvement in the existing supply chain configurations.
- LCA studies show that there is a considerable environmental benefit of using regenerative textiles as well as regenerative agriculture.

- The regenerative cotton can be obtained through recycle/recover route or through the regenerative agriculture route.
- LCA studies on regenerative cotton are majorly focused on recycled cotton, recover cotton, and the reuse of cotton-based clothes.

Future scope

The review observed that there are negligible LCA studies in the open literature on cotton obtained through the regenerative agriculture route. There exists a future scope to conduct life cycle assessment studies on cotton obtained through the regenerative agriculture route. Conducting such studies will help to create a life cycle inventory for future studies and add to the existing knowledge in this context.

References

1. Agnew JM, Leonard JJ (2003) The physical properties of compost. Compos Sci Util 11(3):238–264. https://doi.org/10.1080/1065657X.2003.10702132
2. Angelstam M, Artman A, Hanström J, Rodríguez DM, Uskali D (2016) Viscose vs cotton T-shirts, p 25
3. Arena M, Azzone G, Conte A (2013) A streamlined LCA framework to support early decision making in vehicle development. J Clean Prod 41:105–113. https://doi.org/10.1016/j.jclepro.2012.09.031
4. Avadí A, Marcin M, Biard Y, Renou A, Gourlot JP, Basset-Mens C (2020) Life cycle assessment of organic and conventional non-Bt cotton products from Mali. Int J Life Cycle Assess 25(4):678–697. https://doi.org/10.1007/s11367-020-01731-x
5. Babel N, Toma A, Akhil S (2019) Comparative life cycle assessment (LCA) of second-hand clothing vs new clothing, p 59
6. Baydar G, Ciliz N, Mammadov A (2015) Life cycle assessment of cotton textile products in Turkey. Resour Conserv Recycl 104:213–223. https://doi.org/10.1016/j.resconrec.2015.08.007
7. Bjørn A, Moltesen A, Laurent A, Owsianiak M, Corona A, Birkved M, Hauschild, MZ (2018) Life cycle inventory analysis. In: Hauschild MZ, Rosenbaum RK, Olsen SI (eds) Life cycle assessment. Springer International Publishing, pp 117–165. https://doi.org/10.1007/978-3-319-56475-3_9
8. Bodin R (2016) To reuse or to incinerate? A case study of the environmental impacts of two alternative waste management strategies for household textile waste in nine municipalities in northern Stockholm, Sweden [The Royal Institute of Technology (KTH)]. http://www.diva-portal.org/smash/get/diva2:972626/FULLTEXT01.pdf
9. Busari MA, Kukal SS, Kaur A, Bhatt R, Dulazi AA (2015) Conservation tillage impacts on soil, crop and the environment. Int Soil Water Conserv Res 3(2):119–129. https://doi.org/10.1016/j.iswcr.2015.05.002
10. Caputo P, Zagarella F, Cusenza MA, Mistretta M, Cellura M (2020) Energy-environmental assessment of the UIA-OpenAgri case study as urban regeneration project through agriculture. Sci Total Environ 729:138819. https://doi.org/10.1016/j.scitotenv.2020.138819
11. Castellazzi MS, Wood GA, Burgess PJ, Morris J, Conrad KF, Perry JN (2008) A systematic representation of crop rotations. Agric Syst 97(1–2):26–33. https://doi.org/10.1016/j.agsy.2007.10.006
12. Colley TA, Olsen SI, Birkved M, Hauschild MZ (2020) Delta life cycle assessment of regenerative agriculture in a sheep farming system. Integr Environ Assess Manag 16(2):282–290. https://doi.org/10.1002/ieam.4238

13. Dias T, Dukes A, Antunes PM (2015) Accounting for soil biotic effects on soil health and crop productivity in the design of crop rotations. J Sci Food Agric 95(3):447–454. https://doi.org/10.1002/jsfa.6565
14. Djaman K, Allen S, Djaman DS, Koudahe K, Irmak S, Puppala N, Darapuneni MK, Angadi SV (2022) Planting date and plant density effects on maize growth, yield and water use efficiency. Environ Challenges 6:100417. https://doi.org/10.1016/j.envc.2021.100417
15. Emara Y, Siegert M-W, Lehmann A, Finkbeiner M (2018) Life cycle management in the pharmaceutical industry using an applicable and robust LCA-based environmental sustainability assessment approach. In: Benetto E, Gericke K, Guiton M (eds) Designing sustainable technologies, products and policies. Springer International Publishing, pp 79–88. https://doi.org/10.1007/978-3-319-66981-6_9
16. Farrant L, Olsen SI, Wangel A (2010) Environmental benefits from reusing clothes. Int J Life Cycle Assess 15(7):726–736. https://doi.org/10.1007/s11367-010-0197-y
17. Fidan FŞ, Aydoğan EK, Uzal N (2021) An integrated life cycle assessment approach for denim fabric production using recycled cotton fibers and combined heat and power plant. J Clean Prod 287:125439
18. Finkbeiner M, Inaba A, Tan R, Christiansen K, Klüppel H-J (2006) The new international standards for life cycle assessment: ISO 14040 and ISO 14044. Int J Life Cycle Assess 11(2):80–85. https://doi.org/10.1065/lca2006.02.002
19. Gattinger A, Jawtusch J, Muller A, Mäder P (2011) A climate smart solution?, p 24
20. Giller KE, Hijbeek R, Andersson JA, Sumberg J (2021) Regenerative agriculture: an agronomic perspective. Outlook Agric 50(1):13–25. https://doi.org/10.1177/0030727021998063
21. Gomiero T, Paoletti MG, Pimentel D (2008) Energy and environmental issues in organic and conventional agriculture. Crit Rev Plant Sci 27(4):239–254. https://doi.org/10.1080/07352680802225456
22. Guinée JB, Udo de Haes HA, Huppes G (1993) Quantitative life cycle assessment of products. J Clean Prod 1(1):3–13. https://doi.org/10.1016/0959-6526(93)90027-9
23. Hauschild MZ, Rosenbaum RK, Olsen S (2018) Life cycle assessment. Springer
24. ISO 14040:2006—Environmental management—Life cycle assessment—Principles and framework (2006). https://www.iso.org/standard/37456.html
25. Jacquemin L, Pontalier P-Y, Sablayrolles C (2012) Life cycle assessment (LCA) applied to the process industry: a review. Int J Life Cycle Assess 17(8):1028–1041. https://doi.org/10.1007/s11367-012-0432-9
26. Joshi S (1999) Product environmental life-cycle assessment using input-output techniques. J Ind Ecol 3(2–3):95–120. https://doi.org/10.1162/108819899569449
27. Koudahe K, Allen SC, Djaman K (2022) Critical review of the impact of cover crops on soil properties. Int Soil Water Conserv Res 10(3):343–354. https://doi.org/10.1016/j.iswcr.2022.03.003
28. La Rosa1 AD, Grammatikos SA (2019) Comparative life cycle assessment of cotton and other natural fibers for textile applications. Fibers 7(12). https://doi.org/10.3390/FIB7120101
29. LCA of recycling cotton (No. 75) (2016). Miljögiraff
30. Lotter DW (2003) Organic agriculture. J Sustain Agric 21(4):59–128. https://doi.org/10.1300/J064v21n04_06
31. Marconi M, Favi C (2020) Eco-design teaching initiative within a manufacturing company based on LCA analysis of company product portfolio. J Clean Prod 242:118424. https://doi.org/10.1016/j.jclepro.2019.118424
32. Moursy MAM, ElFetyany M, Meleha AMI, El-Bialy MA (2023) Productivity and profitability of modern irrigation methods through the application of on-farm drip irrigation on some crops in the Northern Nile Delta of Egypt. Alex Eng J 62:349–356. https://doi.org/10.1016/j.aej.2022.06.063
33. Moyer J, Smith A, Rui Y, Hayden J (2020) Regenerative agriculutre and the soil carbon solution. Rodale Institute, pp 1–38. https://rodaleinstitute.org/wp-content/uploads/Rodale-Soil-Carbon-White-Paper_v8.pdf

34. Moyer L, Gupta SM (1997) Environmental concerns and recycling/disassembly efforts in the electronics industry. J Electron Manuf 07(01):1–22. https://doi.org/10.1142/S0960313197000026
35. Mubvumba P, DeLaune PB, Hons FM (2022) Enhancing long-term no-till wheat systems with cover crops and flash grazing. Soil Secur 8:100067. https://doi.org/10.1016/j.soisec.2022.100067
36. Nellström M, Saric M (2019) A comparative life cycle assessment of Nudie Jeans' repair and reuse concept [Chalmers University of Technology]. https://odr.chalmers.se/bitstream/20.500.12380/300088/1/E2019_113.pdf
37. Ness B, Urbel-Piirsalu E, Anderberg S, Olsson L (2007) Categorising tools for sustainability assessment. Ecol Econ 60(3):498–508. https://doi.org/10.1016/j.ecolecon.2006.07.023
38. Newton P, Civita N, Frankel-Goldwater L, Bartel K, Johns C (2020) What is regenerative agriculture? A review of scholar and practitioner definitions based on processes and outcomes. Front Sustain Food Syst 4:577723. https://doi.org/10.3389/fsufs.2020.577723
39. Noor Shah A, Wu Y, Iqbal J, Tanveer M, Bashir S, Ur Rahman S, Hafeez A, Ali S, Ma X, Alotaibi SS, Shehawi AE, Yang G (2021) Nitrogen and plant density effects on growth, yield performance of two different cotton cultivars from different origin. J King Saud Univ-Sci 33(6):101512. https://doi.org/10.1016/j.jksus.2021.101512
40. Palme A, Peterson A, de la Motte H, Theliander H, Brelid H (2017) Development of an efficient route for combined recycling of PET and cotton from mixed fabrics. Text Cloth Sustain 3(1):4. https://doi.org/10.1186/s40689-017-0026-9
41. Pegoretti T dos S, Mathieux F, Evrard D, Brissaud D, Arruda JR de F (2014) Use of recycled natural fibres in industrial products: a comparative LCA case study on acoustic components in the Brazilian automotive sector. Resour Conserv Recycl 84:1–14
42. Periyasamy AP, Wiener J, Militky J (2017) Life-cycle assessment of denim. Sustainability in denim. Elsevier, pp 83–110. https://doi.org/10.1016/B978-0-08-102043-2.00004-6
43. Peters GM, Sandin G, Spak B (2019a) Environmental prospects for mixed textile recycling in Sweden. ACS Sustain Chem Eng 7(13):11682–11690. https://doi.org/10.1021/acssuschemeng.9b01742
44. Peters G, Sandin G, Spak B, Roos S (2019b) LCA on fast and slow garment prototypes. https://research.chalmers.se/publication/506725/file/506725_Fulltext.pdf
45. Peters G, Spak B, Sandin G (2019c) LCA on recycling of blended fiber fabrics, p 45
46. Pigosso DCA, Zanette ET, Filho AG, Ometto AR, Rozenfeld H (2010) Ecodesign methods focused on remanufacturing. J Clean Prod 18(1):21–31. https://doi.org/10.1016/j.jclepro.2009.09.005
47. Pool S, Francés F, Garcia-Prats A, Puertes C, Pulido-Velazquez M, Sanchis-Ibor C, Schirmer M, Yang H, Jiménez-Martínez J (2022) Impact of a transformation from flood to drip irrigation on groundwater recharge and nitrogen leaching under variable climatic conditions. Sci Total Environ 825:153805. https://doi.org/10.1016/j.scitotenv.2022.153805
48. Rashwan RS, Hammad DM (2020) Toxic effect of Spirulina platensis and Sargassum vulgar as natural pesticides on survival and biological characteristics of cotton leaf worm Spodoptera littoralis. Sci Afr 8:e00323. https://doi.org/10.1016/j.sciaf.2020.e00323
49. Rebitzer G, Ekvall T, Frischknecht R, Hunkeler D, Norris G, Rydberg T (2004) Life cycle assessment Part 1: framework, goal and scope definition, inventory analysis, and applications. 30(5):20
50. Recanati F, Arrigoni A, Scaccabarozzi G, Marveggio D, Melià P, Dotelli G (2018) LCA towards sustainable agriculture: the case study of Cupuaçu Jam from agroforestry. Procedia CIRP 69:557–561. https://doi.org/10.1016/j.procir.2017.11.003
51. Regenerative Organic Certified (2021) Framework for regenerative organic certified. https://regenorganic.org/wp-content/uploads/2021/02/ROC_ROC_STD_FR_v5.pdf
52. Rhodes CJ (2017) The imperative for regenerative agriculture. Sci Prog 100(1):80–129. https://doi.org/10.3184/003685017X14876775256165
53. Rosson L, Byrne N (2020) Comparative gate-to-gate life cycle assessment for the alkali and acid pre-treatment step in the chemical recycling of waste cotton. Sustainability 12(20):8613. https://doi.org/10.3390/su12208613

54. Rowntree JE, Stanley PL, Maciel ICF, Thorbecke M, Rosenzweig ST, Hancock DW, Guzman A, Raven MR (2020) Ecosystem impacts and productive capacity of a multi-species pastured livestock system. Front Sustain Food Syst 4:544984. https://doi.org/10.3389/fsufs.2020.544984
55. Rybaczewska-Blażejowska M, Palekhov D (2018) Life cycle assessment (LCA) in environmental impact assessment (EIA): principles and practical implications for industrial projects. Management 22(1):138–153. https://doi.org/10.2478/manment-2018-0010
56. Saravanan G (2022) Plants and phytochemical activity as botanical pesticides for sustainable agricultural crop production in India-MiniReview. J Agric Food Res 9:100345. https://doi.org/10.1016/j.jafr.2022.100345
57. Schmidt A, Watson D, Roos S, Askham C, Poulsen PB (2016) Gaining benefits from discarded textiles LCA of different treatment pathways. Norden. https://norden.diva-portal.org/smash/get/diva2:957517/FULLTEXT02.pdf
58. Selim M (2019) A review of advantages, disadvantages and challenges of crop rotations. Egypt J Agron. https://doi.org/10.21608/agro.2019.6606.1139
59. Shen L, Worrell E, Patel MK (2010) Open-loop recycling: a LCA case study of PET bottle-to-fibre recycling. Resour Conserv Recycl 55(1):34–52. https://doi.org/10.1016/j.resconrec.2010.06.014
60. Spathas T (2017) The environmental performance of high value recycling for the fashion industry [Chalmers University of Technology]. https://publications.lib.chalmers.se/records/fulltext/250175/250175.pdf
61. Storm BK (2017) Production of recyclates—compared with virgin plastics—a LCA study. MATEC Web Conf 112:04024. https://doi.org/10.1051/matecconf/201711204024
62. van Straten B, Ligtelijn S, Droog L, Putman E, Dankelman J, Weiland NHS, Horeman T (2021) A life cycle assessment of reprocessing face masks during the Covid-19 pandemic. Sci Rep 11(1):17680. https://doi.org/10.1038/s41598-021-97188-5
63. Telles TS, Reydon BP, Maia AG (2018) Effects of no-tillage on agricultural land values in Brazil. Land Use Policy 76:124–129. https://doi.org/10.1016/j.landusepol.2018.04.053
64. Thorbecke M, Dettling J (2019) Carbon footprint evaluation of regenerative grazing at white oak pastures. Quantis. https://blog.whiteoakpastures.com/hubfs/WOP-LCA-Quantis-2019.pdf
65. Turrillas FAE, Guardia M de la (2017) Environmental impact of recover cotton in textile industry. Resour Conserv Recycl 116:107–115
66. Woolridge AC, Ward GD, Phillips PS, Collins M, Gandy S (2006) Life cycle assessment for reuse/recycling of donated waste textiles compared to use of virgin material: an UK energy saving perspective. Resour Conserv Recycl 46(1):94–103
67. Wu Y, Bian S, Liu Z, Wang L, Wang Y, Xu W, Zhou Y (2021) Drip irrigation incorporating water conservation measures: effects on soil water–nitrogen utilization, root traits and grain production of spring maize in semi-arid areas. J Integr Agric 20(12):3127–3142. https://doi.org/10.1016/S2095-3119(20)63314-7
68. Xing T (2022) Increasing soil microbial biomass nitrogen in crop rotation systems by improving nitrogen resources under nitrogen application, p 13
69. Yang H, Chai Q, Yin W, Hu F, Qin A, Fan Z, Yu A, Zhao C, Fan H (2022) Yield photosynthesis and leaf anatomy of maize in inter- and mono-cropping systems at varying plant densities. Crop J 10(3):893–903. https://doi.org/10.1016/j.cj.2021.09.010
70. Yousef S, Tatariants M, Tichonovas M, Kliucininkas L, Lukošiūtė SI, Yan L (2020) Sustainable green technology for recovery of cotton fibers and polyester from textile waste. J Clean Prod 254. https://doi.org/10.1016/j.jclepro.2020.120078
71. Zhang X, Liu H, Ma X, Zhou G, Ruan H, Cui H, Pang J, SIFFAT Ullah K, Zong N, Wang R, Leng P, Zhao J (2022) Genome-wide association study and metabolic pathway prediction of barrenness in maize as a response to high planting density. J Integr Agric S2095311922001678. https://doi.org/10.1016/j.jia.2022.08.089

Life Cycle Assessment of Textile Fibres in Brazil: A Literature Review

Juliana F. Picoli, Thais C. Guimarães, and Marina P. Colerato

Abstract This chapter presents a literature review of LCA studies of the three most used fibres in the textile industry: polyester, cotton, and viscose. The article provides the current state of the art and recommendations for future research in the Brazilian textile sector. Through an extensive literature review of LCA studies on the environmental impacts of textile fibres, it was possible to assess and identify the critical points of five categories of environmental impacts: climate change, water consumption, toxicity, land use, and energy use. As a result, 31 studies were evaluated, of which 26% are Brazilian studies and 74% international studies. Cotton is the most studied fibre (31 studies), followed by polyester (11 studies) and viscose (11 studies). The most assessed impact categories are climate change, water consumption, and energy use. The review exposes the wide variation in results observed between different studies. There is also an absence of methodological standard and gaps in some areas of knowledge, which makes it difficult to consistently compare data and the environmental profile between fibres. In conclusion, it is evident that managing socio-environmental impacts throughout the life cycle of textile products—from the extraction of natural resources, through design, manufacture, and use, to the end-of-life—is essential for implementing processes towards more sustainable products, fostering best practices, and joint actions, among the various players in the textile sector.

Keywords Textile industry · Environmental impact · Life cycle analysis (LCA) · Cotton · Viscose · Polyester · Apparel · Sustainable fashion

J. F. Picoli (✉) · T. C. Guimarães
Center for Sustainability Studies, Getulio Vargas Foundation, Av. 9 de Julho, 2029, Bela Vista, São Paulo, SP 202901313-902, Brazil
e-mail: juliana.picoli@fgv.br

M. P. Colerato
Modefica, Rua Olavo Bilac, 257, Vila Sofia, São Paulo, SP 04671-050, Brazil

S. S. Muthu (ed.), *Progress on Life Cycle Assessment in Textiles and Clothing*, Textile Science and Clothing Technology,
https://doi.org/10.1007/978-981-19-9634-4_3

1 Introduction

Driven by population growth and Fast-Fashion, the production of textile fibres has more than doubled in the last 20 years. In Brazil, 8.9 billion pieces are made annually, equivalent, on average, to 37.3 pieces/hab/year [3]. Meeting the demand for raw materials and labour in this entire fashion value chain leads to a succession of socio-environmental impacts. On the other hand, the increase in awareness and concern about unsustainable production and consumption coupled with the goals imposed by climate change, have been demanding a transformation of the textile industry towards more sustainable production and consumption systems. The existence of metrics that give rise to key performance indicators is essential for companies to establish corporate sustainability goals. In this sense, Life Cycle Assessment (LCA) has been the dominant tool for estimating the environmental impacts of products. With a systemic view of the entire value chain, LCA contributes so that decisions based on scientific data are made, actions are implemented, and results are monitored.

This chapter presents a literature review of LCA studies of the three most used fibres in the textile industry: polyester, cotton, and viscose. The study is part of the Fashion Threads Project and provides the current state of the art and points out areas for future research in the textile sector. The Project is led by Modefica, in partnership with the Center for Sustainability Studies of Fundação Getulio Vargas (FGVces) and Regenerate Fashion and its final report can be accessed at: https://reports.modefica.com.br/fashion-threads/. The report "Fashion Threads: Systemic Perspectives for Circularity" is the first Brazilian publication responsible for analysing, qualitatively and quantitatively, the socio-environmental impacts of fibres in the fashion industry.

The revised publications presented in this chapter provide an overview of the environmental impacts along the value chain and allow to identify the hotspots of the analysed products and the main opportunities for reducing environmental impacts in this chain, fostering best practices and joint actions among the various players in the textile sector. The review, however, exposes the wide variation in results observed between different studies. There is also an absence of methodological standards and gaps in some areas of knowledge, which makes it difficult to consistently compare data and the environmental profile between fibres.

In the following section, an overview of the textile market and the profile of this industry in Brazil are presented. The main stages of the life cycle of a piece of cloth are presented in Sect. 3, from obtaining raw materials to its disposal. A further section is devoted to assessing the literature review of LCA studies, pointing out what is already known and the critical points regarding selected sustainability aspects, such as climate change, land use, water resources, and toxicity. Finally, the subsequent sections point out the main gaps found and the main recommendations and final considerations of this study.

2 Textile Production: The Brazilian Context

Almost two hundred years old, the Brazilian textile sector has the most complete production chain in the West: from the production of fibres—such as cotton farming—to spinning, weaving, processing, manufacturing, as well as retail and fashion shows. A world reference in jeanswear, homewear, and beach fashion, Brazil has also stood out in recent years in the fitness and lingerie segments [3]. About 8.9 billion clothing pieces are made annually in Brazil. On average, that amounts to 37.3 pieces/inhabitant/year [3].

The Brazilian textile industry is the 4th largest denim and knitwear global producer and stands out for being the 4th largest denim consumer. Brazil is among the 10th largest textile producer in the world, with production of approximately 2 million tons and US$13 billion dollars [40].

Another peculiarity of national fashion is its dispersion. There are 24.6 thousand companies in the sector [33], 96.8% of which are micro and small enterprises [2]. The Southeast region concentrates 46.8% of all companies in the country's textile and clothing sector, with a large concentration (26%) in São Paulo's state. 31.5% of the companies are in the South, followed by the Northeast, with 14.4%, the Midwest, with 6.2% and the North, with 1.1% [33].

The Brazilian textile and apparel industry is the second largest employer in the country's manufacturing field, with almost 1.4 million formal jobs. The greatest concentration of jobs is found at the beginning of the production chain, in manufacturing of made-up articles [33]. In Brazil, production is more fragmented, with more suppliers working on the fabrication of a single product, resulting in greater difficulty in tracking the socio-environmental impacts of the production process [44].

Several social issues are associated with the sector. They include (but are not limited to) poor working conditions, slave-like work, subcontracting, lack of protection for the use of pesticides and chemicals, and child labour [44].

Textile production is led by cotton fibre, which represents more than 90% of the national market. Cotton is also the most used fibre in the Brazilian fashion industry, representing about 40% of the raw material used in women's fashion and 70% in men's [42].

The national production of polyester also stands out. In 2021, it accounted for 73% of all nationally produced synthetic fibres, with an annual output of 159 thousand tons [6].

The export volume of raw cotton to some countries is notorious, such as China (31%), Vietnam (13%), and Indonesia (13%), as well as the import volume of synthetic fibres from China (34%), South Korea (12%), Vietnam (12%), and Bangladesh (12%) [17]. Brazil is also a major exporter of soluble cellulose, a component for the production of viscose. Its primary consumer market is China, the two major soluble cellulose producers in Brazil, Bracell, and Jari Celulose serve the Chinese market with 100 and 69% of its production [44].

3 Textile Life Cycle

The Life Cycle Assessment (LCA) is a consistent and effective tool to efficiently quantify the environmental impacts associated with the processes and activities throughout the value chain, as well as to provide inputs regarding more efficient management of processes [4, 5]. In fashion, an LCA study can, for example, confirm or deny whether recycling a garment is genuinely environmentally advantageous.

To quantify an item's impacts over the life cycle of a garment, it is necessary to understand its constituting steps and processes. Figure 1 shows the life cycle of a piece in a simplified way, from obtaining raw materials to its disposal. It must be taken into account that, in addition to distribution services, there is natural resource, input, and energy consumption at all stages. There are also air, water, and soil emissions at all life cycle stages—such as atmospheric emissions of GHG and toxic agents' disposal in water bodies.

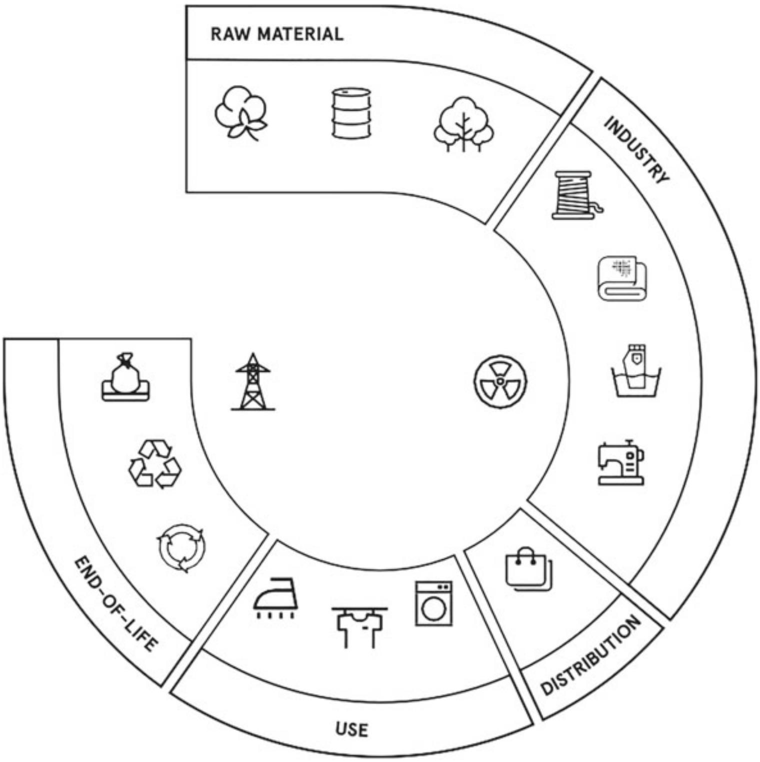


Fig. 1 A garment's life cycle. *Source* Own elaboration

3.1 Raw Material Production

The life cycle of a garment begins with fibre production, an essential raw material for its manufacture. In this chapter, we will detail the production of cotton, polyester, and viscose fibres.

3.1.1 Cotton

Cotton fibre begins its journey in the field, with soil preparation, seeding, followed by cultivation and harvesting. After mechanised harvesting, the cotton processing process takes place. In this process, two valuable co-products, seed and fibre, are separated from each other and from the waste [67]. The modules of cotton then go on to spinning factories.

According to a National Supply Company (Companhia Nacional de Abastecimento) survey, the average yield of seed cotton in the 2020/2021 harvest was 4.23 t/ha, with a fibre yield of 40% [22]. The amounts of nutrients N, P, and K used in cotton can vary depending on the availability of nutrients in the soil and the producer's management. National values are in the order of 110 kg N/ha, 60 kg P_2O_5/ha, and 40 kg K_2O/ha [46].

Due to its high susceptibility to pests and diseases, pesticides (mainly insecticides, herbicides, and fungicides) in cotton culture are quite relevant. In Brazil, cotton is the fourth most pesticide-consuming crop, accounting for approximately 10% of the total volume of pesticides used nationally [14]. It has an average application of 28 L of pesticides per hectare of cotton [8]. The impact of pesticide use is worrisome due to the high potential to affect human health and the environment. It can cause contamination of surface and underground waters, bee mortality, intoxication, spontaneous abortion, and cancer in human beings [8].

Like all crops, cotton's production expansion may also be linked to land-use impacts and deforestation risks. When analysing the 2021 harvest, in almost all the states where cotton was planted, there was also an increase in the total crop area compared to the previous season. This is especially true for the States of Mato Grosso (MT) and Bahia (BA), which represent about 90% of the total cotton farming area. MT is the top producing state, and in the last harvest, it had a crop area increase of 18.6%, totalling an area of 1.14 million hectares. There was an increase of 15.4% of the crop area in Bahia, reaching an extension of 307.7 thousand hectares [22].

On the other hand, the country has invested in traceability and certification to guarantee production with less environmental impact. Brazil is the world's largest producer of certified Better Cotton Initiative (BCI) plume, accounting for about 36% of BCI cotton's total volume [7, 11]. In the 2019/20 harvest, more than 75% of cotton fibres were produced under the socio-environmental criteria of the BCI/ABR (Algodão Brasileiro Responsável—Responsible Brazilian Cotton) certification, corresponding to 1.25 million hectares and 2.2 million tons [7].

It is worth mentioning that there is a predominance of non-irrigated cotton cultivation in Brazil, with only 8% of irrigated area [7, 66]. Brazil is the world's fourth largest producer of cotton lint and the world's second largest exporter, ranking first in rainfed productivity [7]. This peculiarity of our national production drastically reduces water consumption during a garment's life cycle.

3.1.2 Polyester

The polyester production chain starts with oil refining, obtaining naphtha, which, among other products, generates the raw materials for para-xylene (P-Xylene) and ethylene. These are transformed into terephthalic acid (PTA) and mono-ethylene glycol 30 (MEG). Another production route uses Dimethyl Terephthalate (DMT) and mono-ethylene glycol (MEG) [6, 13].

These chemicals then go through the polycondensation process and generate the polyester thermoplastic resin. The polyester is then stretched and extruded, thus producing the polyester filaments that are finally sent to the textile factories, following their life cycle [6, 13].

Polyester fibre features interesting characteristics, such as reduced fabric wrinkling tendency, high resistance to moisture and chemical agents, non-allergenic and high tensile strength. However, polyester fibre is also strongly associated with microplastics in the seas and oceans [27].

Despite being from petroleum, a non-renewable and polluting source, one of the apparent advantages of this fibre is that it is recyclable. The percentage of recycled polyester made from PET plastic bottles increased from 8%, in 2007, to 22%, in 2019. According to the last PET Recycling Census in Brazil, 311 thousand tons of PET were recycled in 2019 (55% of total production). Of this total, about 1/5 progressed to the textile industry [1]. The recycled raw material replaces the one made from oil, with savings in materials and energy. However, this account can result in a zero-sum game, as the production of recycled polyester from PET bottles requires a continuous flow of virgin plastic production for PET bottles in the first place. Simultaneously, dependency on plastics of other industries can divert attention to the search for solutions to polyester textile waste, hindering the evolution of a circular textile-to-textile system [31].

3.1.3 Viscose

Viscose is an artificial fibre produced from (soluble) cellulose with a high alpha-cellulose[1] content.

Soluble cellulose can be produced through batches and follows the same traditional chemical processes as cellulose production for paper (kraft process) [68]. It

[1] The soluble cellulose used for viscose production has an alpha-cellulose content between 90 and 92%, while cellulose for paper usually has 87% [68].

is worth mentioning that this process can be self-sufficient in energy through wood biomass (bark and branches).

Most of the world's production of soluble cellulose (77%) is used for viscose manufacturing. 40% of the world's capacity potential is located in Asia [29]. Brazil is also among the top 10 producers of soluble cellulose, representing about 11% of world production in 2019 [63], with a highlight to the company Bracell with an installed capacity of 750,000 tons [16].

Viscose production process begins with the saturation of cellulose by caustic soda. The material is then exposed to air, so that controlled oxidation of the cellulose chains occurs, converting them into shorter chains. The product obtained is placed in a tank and treated with carbon disulfide, forming groups of ester-xanthate. Again, this material is dissolved in a caustic soda solution, resulting in an insoluble cellulose solution—an intermediate viscous mass called cellulose xanthogenate or viscose. The viscose then undergoes ageing and filtering processes to remove insoluble substances that may cause defects in the filaments. After ageing, it goes through an extrusion and stretching process, forming continuous filaments. These filaments, in turn, are extruded and cut for the production of viscose fibres [13].

The use of chemicals—mainly caustic soda, sulfuric acid, and carbon disulfide—is the most questioned environmental aspect of the viscose production process. Both caustic soda and sulfuric acid are highly corrosive chemicals, dangerous to the work environment, and can cause environmental contamination. Carbon disulfide is another widely used chemical, highly toxic to humans. It can lead to serious health problems, including parkinsonism, heart attack, and stroke [20].

Another relevant environmental aspect is the origin of the wood used in viscose production, which may be related to land-use change and deforestation risks. Just as in cotton cultivation, some initiatives seek to certify suppliers that properly use natural resources and are committed to non-predatory exploitation of forests, such as Forest Stewardship Council® (FSC) and Canopy. Both organisations have made efforts to ensure better forest management in Brazil. However, they recognise the complexity of Brazilian wood production, especially in the north and northeast of the country and its socio-environmental impacts [44].

3.2 Manufacturing and Distribution

After the fibres are produced, they are transported to factories to become yarns, which, in turn, are woven and become fabrics. Once produced, materials undergo a processing process where the dyeing, washing, printing, and finishing operations are carried out. Finally, the finished fabrics are destined for sewing facilities that carry out cutting and sewing, create the garments and distribute them in stores and shops.

Depending on the fibre used, the type of process and the number of inputs used may vary. In general, the high consumption of electricity is very characteristic of this stage, as well as the generation of solid residues (mainly scraps of fabrics generated during cutting and sewing) and effluents (mostly during the dyeing process) [49].

Fabric losses in Brazilian factories can reach 20%. It is estimated that the losses in all stages of t-shirt manufacturing are around 50% for cotton, 31% for polyamide, and 29% for polyester. In all cases, the most significant losses happen in cutting and sewing—responsible for 25% of all fibres [66].

From a social perspective, the spinning process, mainly of cotton fibre, generates fine dust associated with workers' chronic respiratory problems. Another problem in the sector is hiring informal labour, especially during the cutting and sewing process.

3.3 Use

Once clothing pieces are done and distributed, it's the consumer's turn to acquire and use them, carrying out washing, drying, and ironing operations several times until finally disposing it off.

The use stage contributes significantly to various environmental impacts and varies according to the habits of each person and even the region where they live. The manner and frequency in which the washing, drying, and ironing processes are carried out depend on several factors: the garment type dictates the use—the frequency of wearing a T-shirt is different from the frequency of wearing a cold jacket; the kind of fibre—polyester can prevent ironing, as it wrinkles a lot less, but it releases microplastics during the washing process; the climate—Brazilian weather allows drying to be done outdoors; type of washing machine—hot wash cycles consume more energy than cold ones, the efficiency of the device can vary, etc.

The survey "Possibilities for Circular Fashion in Brazil—Patterns of Consumption, Use and Disposal of Clothes", carried out by the Fashion Threads Project, provides interesting data about the habits of Brazilians [43]. With 1683 respondents, the survey reveals that:

- 67.1% of respondents use their clothes 2–3 times before washing them;
- 69.4% dry their clothes outdoors;
- 26.1% have the habit of frequently ironing their clothes;
- 78.2% of respondents keep their clothes for 3 years or more before disposal them.

3.4 End-of-Life

The end-of-life of a garment may follow different destinations depending on the degree of information provided to the user and selective collection availability in their region. When discarded in standard trash, the clothes end up in sanitary landfills or open dumps, taking dozens of years to decompose and negatively impacting the environment [44].

The equivalent of about 16 trucks of textile waste is sent to landfills every day (approximately 45 tons), collected in the Brás region in São Paulo [44].

When decomposing, part of the emissions from biodegradable garments—such as cotton and viscose—is related to biogenic carbon emissions. It is estimated that cotton and viscose capture (during the agricultural production phase) and emit (during their decomposition) about 1.5 kg CO_2/kg of fibre [30, 59].

The piece can also be reused if the consumer has destined it for donation or a thrift store. It can also be recycled if there is a collection point. These practices can reduce the consumption of new garments and, therefore, the amount of natural resources and pollutants used in their manufacture.

Although possible, apparel recycling is far from being a reality in the fashion industry. It is estimated that less than 1% of all garments is recycled back into clothing [27]. Among the main challenges are technical barriers such as the lack of separation technologies for mixed fibres and non-technical ones, such as lack of incentives, logistics, collection points, and population habits [56].

The use of mixed fibres and metals (zippers, buttons, etc.) generally hinders the recycling process and decreases the recycled fibres' quality, which becomes shorter, losing financial value [55]. To increase Brazil's recycling rate, it is necessary to invest in the initial stage—the collection process of discarded consumer's material. The building of large sorting centres to separate recyclable materials, increasing selective collection, increasing the number of collecting cooperatives, and environmental education are examples of how to stimulate this circular chain [44].

4 Literature Review of LCA Studies

The assessment of environmental impacts of the three most used fibres in the fashion industry—cotton, polyester, and viscose—was carried out qualitatively through an extensive review of the literature surrounding studies on LCA of textile products.

The literature review addressed the following questions:

- What is the environmental impact of textile fibres?
- What factors influence the environmental impact of textile fibres?
- What are the knowledge gaps in the environmental impact of fibres considering the Brazilian context?

For the literature search, three databases were selected: Science Direct, Google Scholar and the Latin American Journal on Life Cycle Assessment (LALCA). We used the following keywords as search criteria (English and Portuguese): ("LCA" OR "life cycle assessment") AND ("textile" OR "clothing" OR "garment" OR "fashion" OR "apparel") AND ("cotton" OR "viscose" OR "polyester") AND "fibre"; "circular economy" AND ("textile" OR "clothing" OR "garment" OR "fashion" OR "apparel") AND ("cotton" OR "viscose" OR "polyester") AND "fibre"; ("ACV" OU "avaliação do ciclo de vida") E ("têxtil" OU "roupa" OU "fashion" OU "moda") E ("algodão" OU "viscose" OU "poliéster") E "fibra"; "economia circular" E ("têxtil" OU "roupa" OU "fashion" OU "moda") E ("algodão" OU "viscose" OU "poliéster") E "fibra".

Table 1 Environmental impact categories

	Impact category	Description
	Climate change	Climate change that can be directly or indirectly attributed to human activity that alters the composition of the world atmosphere and adds to that caused by climatic variability observed over comparable periods [34]
	Water consumption	Refers to the volume of water captured that does not return to the same hydrographic basin (consumptive water use) [35]
	Toxicity	Refers to the increase in emissions of toxic substances in aquatic and terrestrial ecosystems, which can damage fauna and flora (ecotoxicity) or impact human health due to exposure to toxic substances present in the environment—air, water, or soil (toxicity) [37]
	Land use	Refers to the type of land-use management and the production structure used in a given land in a given period and its transformations [32]
	Energy use	The energy used to produce a material substance or product, taking into account energy used at the manufacturing facility, energy used in producing the materials that are used in the manufacturing facility, and so on [34]

Source Own elaboration

Five important impact categories were selected for the environmental performance assessment: climate change (or carbon footprint), water consumption, toxicity (chemicals), land use, and energy use (Table 1). The chosen impact categories evaluated in this literature review cover the textile industry's main environmental impacts that have been explored by the scientific literature.

It is essential to acknowledge that microplastics' impact—a major environmental problem associated with synthetic fibres—was not considered. The synthetic microfibres released in washing fabrics, such as polyester, nylon, and acrylic, are considered primary sources of microplastics in the oceans [27]. However, to date, there is no environmental impact evaluation method that considers the impact of microplastics on LCA.

The selected articles were organised in a systematic and standardised model. Given each study's specificity, it was necessary to adapt and standardise their respective production flows for 1 kg of fibre in question, thus making it possible to compare the results. This adjustment did not take losses into account during the production process, except when this information was reported in the article. The manipulation of data in this way provided greater consistency, allowing some degree of quantitative comparison. However, although several studies have been identified, different methodologies and assumptions made it challenging to compare data and results.

Once systematised, the articles were analysed in an attempt to identify: the environmental performance reported in the literature (maximum and minimum values, by impact category), the key indicators of each stage (water, energy, and chemical consumption) and the critical points of the process. Also, it was possible to assess where the main information gaps are.

The fibre analyses also consider major environmental impacts associated with each stage of the 3 analysed fibre's life cycle (raw material; spinning and weaving; dyeing; cutting and sewing; transport; use; and disposal) with the intention of assessing which factors influence textile fibres' environmental performance, that is, which are the main critical points identified throughout their life cycle. For this, we consider an impact spectrum of five degrees: very high, high, medium, low, and very low.

Impact degrees of cotton, polyester, and viscose fibres.

Very high	High	Medium	Low	Very low

4.1 *Overview of Selected Studies*

As a result of searching and selecting articles that address this report's research scope, 31 studies were evaluated. The complete list of selected studies can be found in the Appendix.

Of the 39 studies surveyed, 31 were selected, 8 national (26%) and 23 international (74%), as shown in Fig. 2.

Cotton is the most studied fibre covered in all selected articles. Polyester and viscose appear in 35% of the studies. The predominance of national studies on cotton reflects its extraordinary relevance in the Brazilian market, as previously discussed. Also striking is the lack of national LCA studies for the production of viscose.

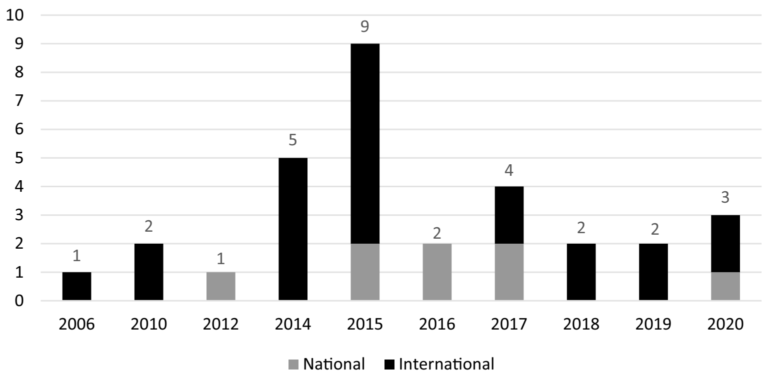


Fig. 2 Number of national and international LCA publications selected (per year). *Source* Own elaboration

According to the studies evaluated, it is also clear that the most studied environmental impact category is climate change (carbon footprint, 27 studies), followed by water consumption (15 studies) and energy use (10 studies).

4.2 Textile Chain's Main Environmental Impacts

The identified data on the environmental impact of fibres are presented in the following subsections. The literature review results indicate the state of the art on the environmental impacts of textile fibres. As mentioned earlier, there is a more generous amount of information about cotton fibre and climate change than the other fibres and impact categories.

The results also indicate a large information gap on a few environmental impacts, and they lack methodological standards. The collected data vary concerning system boundaries, product studied, functional units, impact assessment method, and geographic coverage. This makes it difficult to consistently compare fibres' environmental impacts, even after systematising and standardising the data.

For this reason, the results presented in this section are organised in a particular way. It considers some characteristics of the studies, such as impact category, the origin of the study (national or international) and system boundary (cradle-to-grave or cradle-to-gate). To illustrate variations, the results show not only average values but also the highest and lowest value reported by the literature.

The cradle-to-gate system boundary considers only the cotton production stage. It may also include the manufacturing stages (spinning, weaving, dyeing, and cutting/sewing) and the textile piece distribution. On the other hand, the cradle-to-grave system boundary considers all the steps described in "Section 3. Textile Life Cycle" and, consequently, presents greater environmental impact.

The best way to compare the fibres is through a complete LCA study conducted for this purpose, including all phases of the products' life cycle and the same methodological aspects—functional unit, premises, scope, boundaries, and assessment method. Therefore, the results reported here demonstrate what has already been explored in the literature and the degree of variation between the different outcomes, highlighting the trade-offs.

Figures 3 and 4 consolidate the data identified on the textile chain's environmental impacts. These were the most reported by the literature evaluated in this research, considering the cradle-to-grave and cradle-to-gate scopes, respectively.

The figures elucidate the significant variation between the results presented above. The differences between certain fibre studies are, in some cases, greater than the differences between fibre types. For example, the difference in climate change impact between the maximum and the minimum reported value for cotton fibre is greater than the average difference in this impact between cotton and polyester.

Besides, the data reinforce the importance of documents such as Product Category Rules (PCR) that seek to establish methodologies and premises, which allow consistent comparisons of data and environmental profile between fibres.

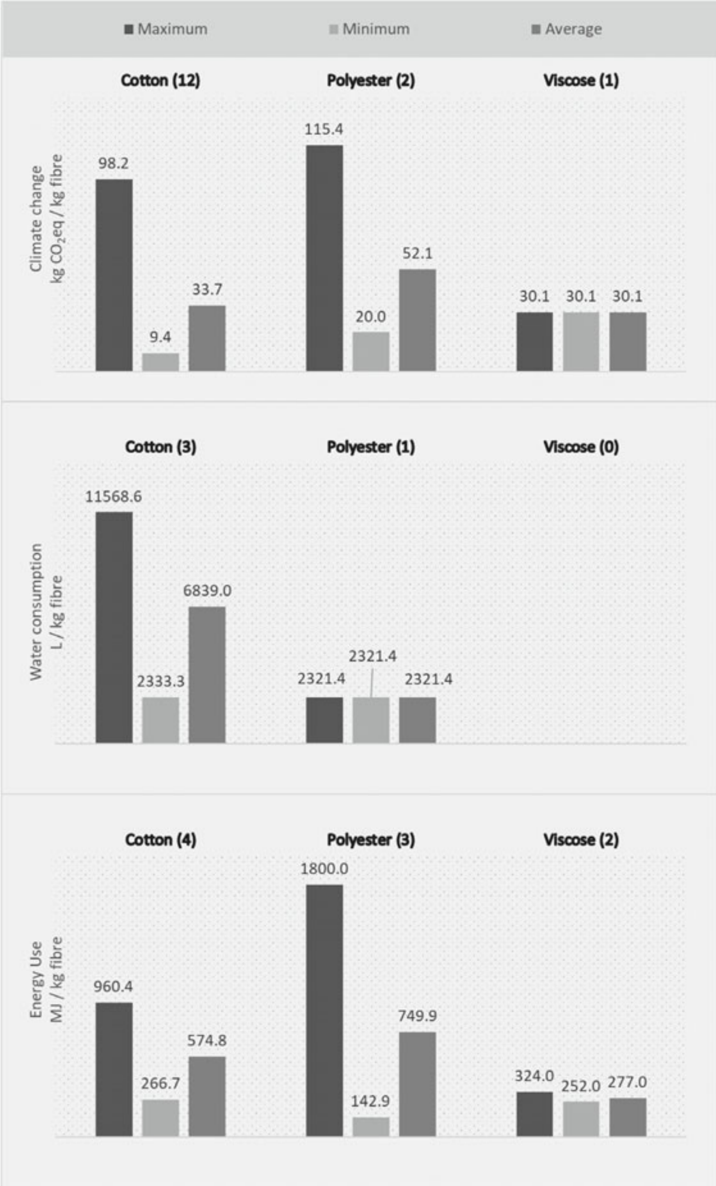


Fig. 3 Main environmental impacts from a textile garment's life cycle (cradle-to-grave). *Note* The figure shows the environmental impact of the three fibres studied, with maximum, minimum, and average values obtained in the literature review. The number in parentheses indicates the number of LCA studies considered. The upper table shows the results for the Climate Change category (in kgCO_2eq/kg fibre); the intermediate table for Water consumption (in L/kg fibre); and the lower frame for energy use (in MJ/kg of fibre)

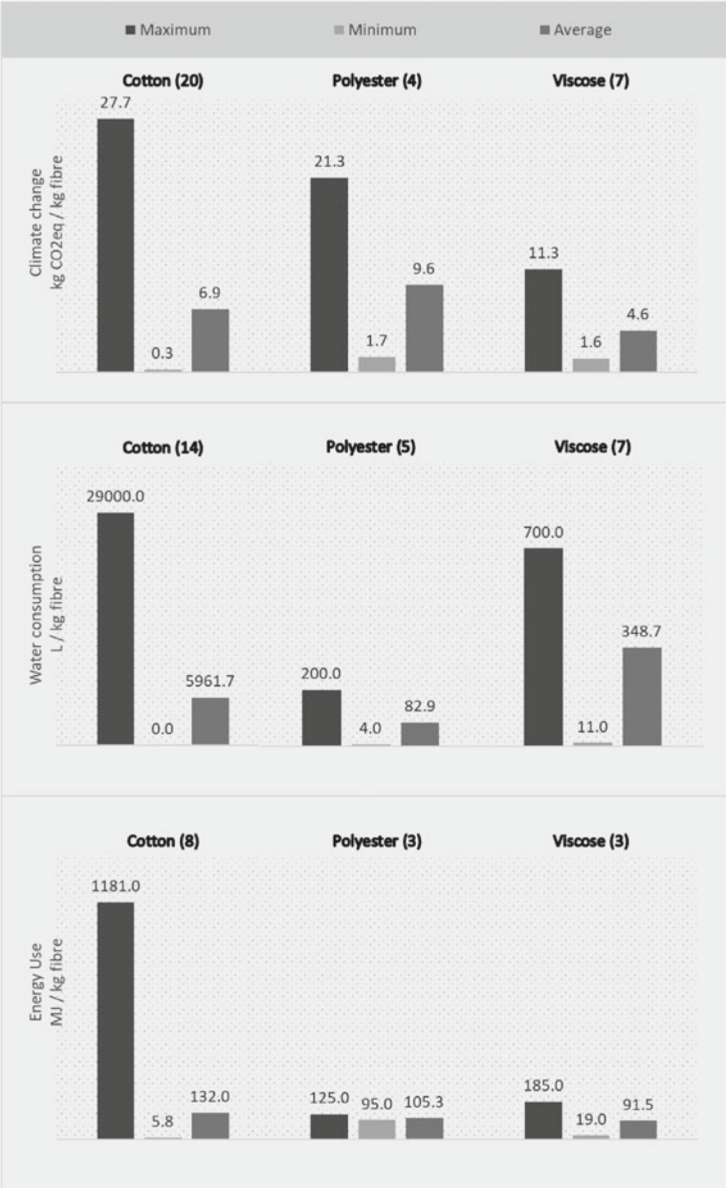


Fig. 4 Main environmental impacts from a textile garment's life cycle (cradle-to-gate). *Note* The figure shows the environmental impact of the three fibres studied, with maximum, minimum, and average values obtained in the literature review. The number in parentheses indicates the number of LCA studies considered. The upper table shows the results for the Climate Change category (in kgCO_2eq/kg fibre); the intermediate table for Water consumption (in L/kg fibre); and the lower frame for energy use (in MJ/kg of fibre). *Source* Own elaboration

The reader must have observed that all the data presented so far are related to the environmental impacts per kg of fibre. As mentioned above, manipulating data in this way provided greater consistency in the evaluation and consolidation of data found in the literature. However, this approach fails to consider some characteristics inherent to each type of fibre, such as weight (mass ratio per unit area), thread thickness, and final product weight.

For example, a polyester t-shirt tends to be lighter than a cotton t-shirt, representing an advantage of synthetic fibres over other types of fibres. This is disregarded when the comparison is made per kg of fibre.

Tables 2 and 3 present the data identified on the environmental impacts of clothing most reported by the literature evaluated in this research, considering the cradle-to-grave and cradle-to-gate approaches, respectively.

Even though the results presented do not allow a direct comparison between the environmental performance of cotton, polyester, and viscose fibres, it is still possible to use LCA results to understand where the chain's main critical points are. Consequently, a discussion about possible, more efficient impact management is offered below.

4.2.1 Cotton

As previously mentioned, cotton is the most studied fibre present in 31 selected articles. Table 4 presents the data identified on a cotton garment's environmental profile, obtained through the systematisation and standardisation of these results.

In the climate change category, a cotton textile piece produced nationally presents average emission values around 32 kg CO_2eq/kg of cotton (cradle-to-grave) and 5 kg CO_2eq/kg of cotton (cradle-to-gate). These values disregard carbon incorporation during photosynthesis and are close to the average values reported by international literature.

On the other hand, the specific characteristics of Brazilian production seem to be very influential in the cotton culture's water consumption. The predominance of non-irrigated cotton production is reflected in the national average values for this category: 2,333 L/kg of cotton (cradle-to-grave) and 1,704 L/kg of cotton (cradle-to-gate). These values are 4 to 5 times lower than the average values reported in international studies. This is a typical Brazilian scenario—more than 70% of the world's cotton is irrigated, and the world average consumption of irrigation water is 10,000 L of water per kg of fibre [66].

It is difficult to draw general conclusions for the impact of toxicity since few studies have evaluated this impact. Considering the international scope, Shen et al. [59] report emissions of 1.7 kg 1.4-DBeq/kg cotton. At the national level, the highest emission is 36.4 kg 1.4-DBeq/kg cotton [60] and the lowest 0.021 kg 1.4-DBeq/kg cotton [45]. This variation may be related to several factors, such as using other types and quantities of chemicals and different methods of estimating the impact.

Similarly, only a few studies have evaluated the impact of land use. Considering the cradle-to-grave approach, the LCA study of a pair of jeans, carried out by the

Table 2 Overview of clothing LCA studies, from cradle-to-grave

Study	Item	Fibre	Weight (g)	Carbon footprint (kg CO_2eq/item)	Energy use (MJ/item)	Water consumption (L/item)
Giasson et al. [30]	T-shirt	Cotton	150.00	3.15	–	–
Vasconcelos et al. [66]	T-shirt	Cotton	150.00	–	40–65	350.00
Allwood et al. [9]	T-shirt	Cotton	250.00	4.00	109.00	–
Wang et al. [69]	T-shirt	Cotton	280.00	8.77	–	–
Chapman [21]	T-shirt	Cotton	250.00	–	194.40	–
Peters et al. [53]	T-shirt	Cotton	110.00	3.00	–	–
Muthu [47, 48]	T-shirt	Cotton	N/A	4.00	–	–
Muthu [48]	T-shirt	Cotton	N/A	2.34	–	–
Muthu [48]	T-shirt	Cotton	250.00	–	240.11	–
Muthu [48]	T-shirt	Cotton	215.00	10.75	–	–
Zhang et al. [70]	T-shirt	Cotton	153.00	6.05	–	1770.00
Vasconcelos et al. [66]	T-shirt	Polyester	140.00	–	35–20	325.00
Peters et al. [53]	T-shirt	Polyester	130.00	15.00	–	–
Muthu [47, 48]	T-shirt	Polyester	N/A	5.00	–	–
Chapman [21]	Blouse	Polyester	55.00	–	68.40	–
Allwood et al. [9]	Blouse	Viscose	200.00	–	51.00	–
Chapman [21]	Blouse	Viscose	200.00	–	50.40	–
Chapman [21]	Blouse	Viscose	200.00	–	64.80	–

(continued)

Levi Strauss & Co. brand, reported an impact of 12 m^2 * year (or 35.3 m^2 * year/kg of fibre, considering a 340-g piece) [39]. National cradle-to-gate studies show a variation from 8.0 to 1.2 m^2 * yr/kg of fibre. As will be discussed below, this impact is greatly influenced by the cotton production phase (mainly by productivity) and, therefore, varies from region to region.

Table 2 (continued)

Study	Item	Fibre	Weight (g)	Carbon footprint (kg CO_2eq/item)	Energy use (MJ/item)	Water consumption (L/item)
Joner et al. [36]	Trouser jeans	Cotton	447.31	9.1–24.8	–	–
Levi Strauss & Co. [39]	Trouser jeans	Cotton	340.00	33.40	–	3781.00
Chapman [21]	Trouser jeans	Polyester	400.00	–	720.00	–
Muthu [48]	Jacket	Polyester	500.00	–	156.39	–
Peters et al. [53]	Dress	Polyester	478.00	10.00	–	–

Source Own elaboration

Table 3 Overview of clothing LCA studies, from cradle to-gate

Study	Item	Fibre	Weight (g)	Carbon footprint (kg CO_2eq/item)	Energy use (MJ/item)	Water consumption (L/item)
Esteve-Turrillas and de la Guardia [28]	T-shirt	Cotton	300.00	2.3–6.9	–	40–4478
Chapman [21]	T-shirt	Cotton	250.00	–	108.00	–
Chapman [21]	T-shirt	Cotton	253.00	–	298.80	–
Peters et al. [53]	T-shirt	Cotton	N/A	1.80	–	–
Peters et al. [53]	T-shirt	Cotton	220.00	2.38	–	–
Muthu [50]	T-shirt	Cotton	250.00	5.46	–	–
Peters et al. [53]	T-shirt	Polyester	130.00	2.55	–	–
Morita et al. [45]	Trouser jeans	Cotton	940.60	7.61	93.00	184.00
Morita et al. [46]	Trouser jeans	Cotton	940.60	7.86	124.00	–
Bongiovanni and Tuninetti [15]	Trouser jeans	Cotton	550.00	4.65	–	–
Chapman [21]	Trouser jeans	Cotton	660.00	9.15	–	–
Chapman [21]	Trouser jeans	Cotton	640.00	6.96	–	–
Muthu [50]	Trouser jeans	Cotton	660.00	17.16	–	–

Source Own elaboration

Table 4 Main environmental impacts from a cotton garment's life cycle

Climate change (kg CO_2eq/kg fibre)					
System boundaries	Studies	Nº	Maximum	Minimum	Average
Cradle-to-grave	International studies	9	98.2	9.4	34.2
	National studies	3	55.4	20.3	32.3
Cradle-to-gate	International studies	15	27.7	0.3	7.3
	National studies	5	8.7	0.3	5.1
Water consumption (L/kg fibre)					
Cradle-to-grave	International studies	2	11,568.6	11,120.6	11,344.6
	National studies	1	2,333.3	2,333.3	2,333.3
Cradle-to-gate	International studies	11	29,000.0	0.0	6,569.9
	National studies	3	4,911.3	6.3	1,704.4
Toxicity (kg 1,4-DBeq/kg fibre)					
Cradle-to-grave	International studies	0	–	–	–
	National studies	0	–	–	–
Cradle-to-gate	International studies	1	1.7	1.7	1.7
	National studies	3	36.4	0.02	12.2
*Land use (m^2 * yr/kg fibre)*					
Cradle-to-grave	International studies	1	35.3	35.3	35.3
	National studies	0	–	–	–
Cradle-to-gate	International studies	3	13.0	8.0	10.5
	National studies	2	8.0	1.2	4.6
Energy use (MJ/kg fibre)					
Cradle-to-grave	International studies	3	960.4	436.0	724.7
	National studies	1	433.3	266.7	350.0
Cradle-to-gate	International studies	5	1,181.0	5.8	138.5
	National studies	3	131.8	75.3	102.0

Source Own elaboration

Finally, the data related to energy use indicate that the production of a cotton textile piece may require, on average, between 102.0 and 138.5 MJ/kg fibre in a cradle-to-gate approach. When evaluating cradle-to-grave, an energy use increase is mentioned, mainly related to the use stage (or users' habits)—with average values ranging from 350 MJ/kg fibre (national studies) to 724.7 MJ/kg fibre (international studies).

Table 5 systematises the leading environmental impacts associated with cotton, at each stage of the life cycle, concerning five environmental impact categories.

As can be seen by the gradual colours, cotton has significant environmental consequences in all impact categories, mainly water consumption, toxicity, and land use. The raw material's production stage generates substantial impacts in the categories related to water consumption and land use. The spinning, weaving, and dyeing stages

Table 5 Overview of main critical points throughout cotton's life cycle

	Climate change	Water consumption	Toxicity	Land use	Energy use
Raw material	Medium	Very high	Very high	Very high	Medium
Spinning and weaving	High	Medium	Low	Low	High
Dyeing	High	Medium	High	Very Low	High
Cutting, sewing and finishing	Low	Low	Low	Very Low	High
Transport	Medium	Low	Very Low	Low	Low
Use	Very high	High	Medium	Medium	Very high
Disposal	Very Low	Very Low	Very Low	High	Very Low

Label	Very high	High	Medium	Low	Very Low

Source Own elaboration

have their major environmental impacts associated with energy use and fossil fuels. Due to washing and drying, the consumer use phase has its most significant effects on climate change and energy use, followed by water consumption.

With regard to the carbon footprint (climate change) in the raw material production stage, the production of fertilisers used in cotton production [47], and the energy used in agriculture for irrigation and ginning [15, 51] are two critical points highlighted in the literature. The global warming potential (GWP) associated with the cotton cultivation and harvesting stage comes mostly from the production of fertilisers and pesticides, followed by nitrous oxide (N_2O) emissions from the application of nitrogen fertiliser on the land and, finally, agricultural machinery operations [10].

Another significant impact concerning the carbon footprint comes from the user's stage, since washing, drying, and ironing generates GHG emissions that contribute to climate change [36, 52]. In a wash and dry cycle, the water temperature and cycle duration are identified as the main determining factors [69]. Analyses of national and international study scenarios point to electric drying and ironing as having higher electricity consumption than machine-washing [36, 50]. It should be noted that electric dryers are not widely used in Brazil, resulting in less electricity consumption and GHG emissions at this stage.

The main impact on water consumption is found in the cotton production stage [51, 54]. The intensive use of water resources is identified in the literature as ecologically unsustainable in several areas. Globally, 53% of cotton fields, which account for 73% of cotton production, are irrigated, with the flood or furrow irrigation system being the most common for cotton cultivation.

Thus, the techniques used in this phase can contribute to the increase or reduction in water consumption. Drip irrigation is estimated to reduce the amount of water used by at least 16–30% compared to surface or ditch irrigation [12]. In the Brazilian case, when it comes to water consumption, cotton has less impact on the production phase than in other locations, since it does not depend on irrigation for cotton cultivation. This technique is usually used in areas where average precipitation does not correspond to the crops' needs.

The spinning and weaving stage, as well as dyeing, also have a certain degree of impact as they consume considerable amounts of water, especially dyeing [54]. The use stage is the second main contributor in terms of water consumption. In this stage, washing is the primary contributor [12]. In scenario analyses, it is estimated that efficient washing machines consume 30% less water during washing than conventional washing machines [52].

The literature also points out that the product colour (e.g., shirt) presents substantial water consumption differences in the washing process, despite little difference in energy use [69]. Thus, the raw material production stage, followed by the consumer use stage, presents the most significant impacts concerning water consumption [52].

Although not part of the scope of this report, the literature reports other impacts associated with water. Raw material production is responsible for the biggest impact due to fertiliser, pesticide, and herbicide contamination of water bodies [51, 54]. Cotton cultivation consumes considerable amounts of agricultural chemicals: while synthetic fertilisers mainly contribute to aquatic eutrophication, pesticides increase the adverse effects of cotton cultivation on fresh water and terrestrial toxicity [51]. Eutrophication, generated by leaching and nutrient-rich soil erosion [52, 54], can be reduced using organic farming techniques [62].

The spinning and weaving, and dyeing stages also have impacts associated with yarn chemical use, water consumption, and disposal [12]. The use stage again appears in the second position in terms of contribution to the environmental impact of the category, which can be related to cleaning products that are not biodegradable and/or based on synthetic components, especially phosphorous compounds [19].

In terms of toxicity, the literature points to the raw material cultivation phase as having the most substantial impact due to the various chemicals used to assist in cotton growth [21]. The chemicals used in cotton farming have adverse effects on human health. Even with known harmful effects, toxic and environmentally persistent pesticides are still widely employed in the Global South [51].

Regarding human health, the stages of dyeing and finishing, yarn preparation, and fibre production are the most impactful, according to the literature. The main factors are linked to fossil fuel use to run processes such as knitting, dyeing, and spinning, besides synthetic fibre production. The toxic impacts of dyeing wastewater are pointed out as a trending topic but of difficult characterisation due to lack of data [54].

After the raw material manufacturing step, the dyeing step is the most toxic due to reactive reagents and pigments, electrical and thermal energy, water and effluents used and generated in the process. Still concerning toxicity, the literature points out that the high values are essentially related to the demand for electricity in the different stages of the life cycle [12].

On land use, the literature points out that cotton cultivation covers large areas of land and production activities due to the number of processes in the formation of fibres and fabrics. In addition to cultivation, land occupation can happen in the forest due to tree-cutting and energy-production activities. The latter is still common in many extractive-based countries [52]. New cotton fields establishment on vulnerable lands is linked to deforestation. Also, the trade-off between cotton use of arable land and food production is mentioned in the literature [51].

Finally, the use stage, which involves washing, drying, and ironing the product, represents the greatest contribution to the use of primary energy and for emissions associated with energy use [21]. Among the production steps, spinning uses the most power, coming from electricity. Dyeing is related to natural gas used to produce steam, fuel for engines and direct heat. The finishing step is linked in the literature to energy consumption for finalising the threads. It pays particular attention to the electrical and thermal energy for washing and drying in this stage [12].

Considering the entire cotton fibre life cycle, the literature points out that cotton cultivation, dyeing, manufacturing, and use stages are the main contributors to environmental impacts. In particular, the use of fertilisers, pesticides; coal, dyes, and auxiliaries used in dyeing; use of electricity at finishing; water and detergent use for washing; and electricity use in spinning were the critical points identified based on the results of life cycle impact assessments. Energy use, chemical and water consumption appear as relevant contributors to most impact categories analysed [50].

4.2.2 Polyester

This report examined 11 articles on polyester fibre's LCA. Only one national study—conducted by Vasconcelos et al. [66]—was found. This study uses the cradle-to-grave approach and details water and energy consumption during the life cycle of cotton, polyamide, and polyester shirts. For the polyester fibre, water consumption is 2,321.4 L/kg fibre and energy use ranges from 250.0 to 142.9 MJ/kg of fibre. Other international studies point to water consumption, ranging from 4 to 200.0 L/kg fibre, from cradle-to-gate. Energy consumption has an average value ranging from 1,118.8 MJ/kg fibre (cradle-to-grave) to 105.3 MJ/kg fibre (cradle-to-gate).

Literature data related to climate impacts indicate that the production of a polyester piece of clothing can emit, on average, between 1.7 and 21.3 kg CO_2eq/kg fibre, considering a cradle-to-gate scenario. When analysing the cradle-to-grave method, an increase in energy use emissions related to the use phase is identified. Average values range from 20.0 to 115.4 kg CO_2eq/kg fibre. Data on impact categories other than water consumption, energy use, and climate change are rarely reported for synthetic fibres [57]. In this research, only Shen and Patel [58] presented results on toxicity. No article has evaluated the influence on land use since this impact is not characteristic of most industrial processes. Table 6 presents the data identified on a polyester garment's environmental profile, obtained through the systematisation and standardisation of our literature review results.

Table 7 systematises the leading environmental impacts associated with polyester, at each stage of the life cycle, concerning five categories of environmental impact.

Table 6 Main environmental impacts from a polyester garment's life cycle

Climate change (kg CO_2eq/kg fibre)					
System boundaries	Studies	Nº	Maximum	Minimum	Average
Cradle-to-grave	International studies	2	115.4	20.0	52.1
	National studies	0	–	–	–
Cradle-to-gate	International studies	4	21.3	1.7	9.6
	National studies	0	–	–	–
Water consumption (L/kg fibre)					
Cradle-to-grave	International studies	0	–	–	–
	National studies	1	2,321.4	2,321.4	2,321.4
Cradle-to-gate	International studies	5	200.0	4.0	82.9
	National studies	0	–	–	–
Toxicity (kg 1,4-DBeq/kg fibre)					
Cradle-to-grave	International studies	0	–	–	–
	National studies	0	–	–	–
Cradle-to-gate	International studies	1	4.4	4.4	4.4
	National studies	0	–	–	–
*Land use (m^2 * yr/kg fibre)*					
Cradle-to-grave	International studies	0	–	–	–
	National studies	0	–	–	–
Cradle-to-gate	International studies	0	–	–	–
	National studies	0	–	–	–
Energy use (MJ/kg fibre)					
Cradle-to-grave	International studies	2	1,800.0	312.8	1,118.8
	National studies	1	250.0	142.9	196.4
Cradle-to-gate	International studies	3	125.0	95.0	105.3
	National studies	0	–	–	–

Source Own elaboration

According to the consulted literature, the raw material and product production phases (spinning, weaving, and dyeing) are potential contributors to the environmental impacts from polyester's life cycle, mainly associated with climate change and intensive use of energy. There are also significant environmental impacts associated with water consumption, and toxicity in raw materials' production stages, spinning and weaving and dyeing.

Concerning the carbon footprint (climate change), one of the points highlighted by the literature is the production of polyester [47], which has Purified Terephthalic Acid (PTA) as a precursor in its formation. The stages of spinning and weaving and dyeing also appear to have high GHG emissions. The use stage, on the other hand, was considered to have a lower environmental impact relative to what is suggested in

Table 7 Overview of main critical points throughout polyester's life cycle

	Climate change	Water consumption	Toxicity	Land use	Energy use
Raw material	Very high	Very Low	Medium	No information	High
Spinning and weaving	High	High	High	No information	High
Dyeing	Very high	High	Very high	No information	High
Cutting, sewing and finishing	Low	No information	Low	No information	High
Transport	Very Low	No information	No information	No information	Low
Use	Low	No information	No information	No information	Very high
Disposal	Very Low	Very Low	No information	High	Low

Label	Very high	High	Medium	Low	Very Low	No information

Source Own elaboration

the classic literature [65], much the same as the transport stage, listed with a relatively low impact regarding the climate [54].

Only one study was found in the literature regarding water consumption with information covering the fibre's entire life cycle [66]. The impact on the fibre production stage is due to water withdrawal from the ecosystem. The spinning and weaving stage's impact is related to the thread preparation, which requires a significant amount of water due to the wet spinning processes used for different fibre materials, be they synthetic or natural. Likewise, the dyeing step, together with the product finish, is a process that consumes considerable amounts of water [54].

Regarding other impacts on water quality, synthetic resin production for synthetic fibres such as polyester affects ecosystem quality. After removing water from the ecosystem for fibre production, processing occurs, thereby returning polluted water to the ecosystem [54]. Despite not presenting information in the compiled literature, the use phase implies releasing a large number of plastic microfibres into the environment [27].

In terms of toxicity, the raw material's production stages, spinning and weaving and dyeing have the most significant impacts. The main critical point is fossil fuel use to produce synthetic fibres and feed the spinning and dyeing processes. Also, there are toxic impacts related to the emission of volatile organic compounds during polyester production and the generation of effluents containing antimony, which harm human health. The dyeing stage also generates toxic wastewater [54].

The land-use category is not explored in detail for polyester in the literature. Therefore, it is not possible to discuss its environmental impacts associated with the life cycle stages.

Finally, regarding energy use, the greatest impact is found in the consumer use stage, with an estimated contribution of 2: 1 for washing and drying, respectively [21]. Next, along with the finish, the dyeing stage is mentioned in the literature as the primary driver of climate change in the global garment industry. The spinning and weaving step is also a significant contributor, albeit to a lesser extent than dyeing [54].

4.2.3 Viscose

In the literature review conducted for this research, we found no national article for viscose fibre. Table 8 presents the data identified on viscose garment's environmental profile, considering the 11 international articles analysed.

Table 8 Overview of main environmental impacts throughout viscose's life cycle

Climate change (kg CO_2eq/kg fibre)					
System boundaries	Studies	Nº	Maximum	Minimum	Average
Cradle-to-grave	International studies	1	30.1	30.1	30.1
	National studies	0	–	–	–
Cradle-to-gate	International studies	7	11.3	1.6	4.6
	National studies	0	–	–	–
Water consumption (L/kg fibre)					
Cradle-to-grave	International studies	0	–	–	–
	National studies	0	–	–	–
Cradle-to-gate	International studies	7	700.0	11.0[a]	348.7
	National studies	0	–	–	–
Toxicity (kg 1,4-DBeq/kg fibre)					
Cradle-to-grave	International studies	0	–	–	–
	National studies	0	–	–	–
Cradle-to-gate	International studies	1	1.5	0.6	1.1
	National studies	0	–	–	–
*Land use (m^2 * yr/kg fibre)*					
Cradle-to-grave	International studies	0	–	–	–
	National studies	0	–	–	–
Cradle-to-gate	International studies	2	8.0	3.3	6.1
	National studies	0	–	–	–
Energy use (MJ/kg fibre)					
Cradle-to-grave	International studies	2	324.0	252.0	277.0
	National studies	0	–	–	–
Cradle-to-gate	International studies	3	185.0	19.0	91.5
	National studies	0	–	–	–

[a] Without considering the cooling water
Source Own elaboration

Most studies present cradle-to-gate system borders, with the categories of climate change and water consumption being the most studied.

On climate change impact, a textile piece of viscose can emit from 1.6 to 11.3 kg CO_2eq/kg of viscose, with average values revolving around 4.6 kg CO_2eq/kg of viscose. Thomas et al. [64] reported emissions of 30.1 kg CO_2eq/kg of viscose throughout its life cycle (cradle-to-grave).

The studies consider that forest production is not irrigated and point to an average water consumption of 348.7 L/kg of fibre for the cradle-to-gate approach in the water category. On the other hand, energy consumption presents average values ranging from 277 MJ/kg fibre (cradle-to-grave) to 91.5 MJ/kg fibre (cradle-to-gate).

Similarly, to cotton fibre, the impact of land use is influenced by wood productivity (the primary raw material for viscose production). Therefore, it varies from region to region. For example, Shen et al. [59] report values between 0.33 and 0.70 ha * yr/t viscose, considering a production site in Asia and Austria, respectively.

Finally, the toxicity impact varies from 0.6 to 1.5 kg 1,4-DBeq/kg viscose, considering production in Asia and Austria, respectively [59].

Table 9 systematises the leading environmental impacts associated with viscose, at each stage of the life cycle, concerning five categories of environmental impact.

There is not much information available in the literature regarding viscose fibre. The impact analyses found are focused on the production part of the raw material. Thus, it was not possible to analyse in detail the other stages of the viscose life cycle concerning the five categories of environmental impact proposed.

Regarding the carbon footprint, despite having less associated GHG emissions than polyester, viscose fibre production has 50% greater estimated emissions than cotton [25].

Concerning water consumption, the water-intensive phases of the viscose fibre production from virgin pulp are cellulose dissolution and viscose fibres' washing

Table 9 Overview of main critical points throughout viscose's life cycle

	Climate change	Water consumption	Toxicity	Land use	Energy use
Raw material	Very high	Medium	Very high	Medium	Very high
Spinning and weaving	No information	Medium	High	No information	High
Dyeing	No information	No information	No information	No information	High
Cutting, sewing and finishing	No information	No information	No information	No information	High
Transport	No information	No information	No information	No information	Low
Use	No information	No information	No information	No information	Medium
Disposal	No information	No information	No information	No information	Low

Label	Very high	High	Medium	Low	Very Low	No information

Source Own elaboration

[59]. The raw material production, that is, the pulp's dissolution, involves large amounts of water. However, no irrigation water is needed in forestry. Water is also used for cooling [51].

Regarding water quality impacts, as it is an artificial fibre, viscose production is intensive in chemical use. The pulp of the wood extracted from the trees undergoes chemical transformation to generate the cellulose fibre and then the viscose threads. The chemicals used, many of them toxic compounds [25], might be dumped into the ecosystem without prior treatment, generating water quality problems [41].

As for toxicity, the viscose production process releases chemical gases—the carbon disulfide (CS_2) and hydrogen sulfide (H_2S). CS_2, in particular, is highly toxic and flammable, being considered an occupational hazard [51].

With regard to land use, viscose fibre is produced by extracting the cellulose found mainly in the wood of fast-growing, low-residue trees, which are easily transformed into pulp. Although other artificial fibres, such as lyocell, also depend on cellulose extraction, viscose production is considered more critical. It is estimated that about 30% of the viscose comes from trees from native and endangered forests, including the Amazon [41].

Finally, in terms of energy use, it is estimated that "approximately 50% of the energy consumed in the production of viscose is of renewable origin ('from the basic feed-stock wood')". Therefore, the production phase consumes less energy [9]. In the use phase, clothes produced from viscose need ironing, which implicates high electrical energy consumption [38].

Thus, despite the small number of studies on viscose's environmental impacts, it is clear that soluble cellulose's production phase makes significant contributions to climate change, toxicity, and energy use impact categories.

5 Gaps Found

After reading and systematising the studies, it was possible to identify gaps in the existing literature, especially in the national context.

As for fibres, most studies are focused on cotton fibre, with a smaller amount also exploring polyester and an even less addressing viscose. There is less detailed information on polyester and viscose studies, for example, on the environmental impact distribution throughout the different stages of the fibre's life cycle. For viscose, the fibre with the least information available in the academic literature, it was necessary to complement the analysis with non-academic literature input. The absence of national LCA studies of viscose production is also worthy of mention.

Concerning the life cycle stages, most studies focus on evaluating impacts with the cradle-to-gate scope. There is a gap of information that considers all the life cycle steps, mainly regarding viscose and polyester. In addition, little information was found in the literature on the cutting and sewing stage, which is not mentioned in several articles.

Of the studies that address the use phase, most are focused on products made from cotton. Also, little information is available regarding the disposal and end-of-life of products. We found no data or empirical studies on Brazilian consumers' behaviour and their habits for using and disposing of clothes.

For environmental impact categories, except for climate change, water and energy use, data on other sorts of impact are rarely reported in the bibliography.

Finally, the data collected from the scientific literature varied in terms of system boundaries (i.e., from cradle-to-gate, from cradle-to-grave, from cradle-to-cradle), product studied (for example, jeans, T-shirt, fibre cotton), functional units (for example 1 kg, 1 ton, 1 jeans), and geographic coverage (Brazil, United Kingdom, United States, among others). Therefore, there is a wide variation in data and information, showing an absence of a methodological standard, making it difficult to compare data and the environmental profile consistently between fibres.

6 Final Remarks and Recommendations

This report sought to analyse, qualitatively and from a life cycle perspective, the environmental impacts of the three fibres evaluated by the Fashion Threads Project: cotton, polyester, and viscose. Through an extensive literature review of LCA studies on the environmental impacts of textile fibres, it was possible to assess and identify the critical points of five categories of environmental impacts: climate change, water consumption, toxicity, land use, and energy use.

This report should therefore be seen as a first analysis aiming at systematising and grouping information on the environmental impacts for the Brazilian context. The results presented indicate state of the art on environmental issues in the fashion industry and strive to advance this agenda's discussions. These results are not exhaustive and offer elements for future discussions with the textile, as well as other sectors of society.

In conclusion, it is evident that managing socio-environmental impacts throughout the life cycle of textile products—from the extraction of natural resources, through design, manufacture, use, to the end-of-life—is essential for implementing processes towards more sustainable products.

Finally, the recommendations presented below are based on the results and lessons learned from the Project:

Regarding scientific studies on the theme, a more in-depth analysis is recommended to better understand and compare the environmental impacts of the studied fibres. Specifically, quantitative LCA studies for each of the evaluated fibres, especially within the Brazilian context of production, use, and disposal. We also recommend the inclusion of the most relevant impact categories (such as climate change, water consumption, toxicity, land, and energy use), the expansion of the system boundaries under study for an assessment from cradle-to-grave, and the use of methodologies and premises in a more standardised way.

Regarding business management, fibre choice and product design are essential, but how fibres and textile parts are produced is equally important. Therefore, implementing the best production and consumption practices across the entire production chain and measuring progress in this direction is paramount. In this sense, we recommend transparency (mainly in communicating impacts and providing data) and tracking supply chains (mainly to verify environmental and social impacts and engage actors to use best practices/technologies.

Regarding the market, there is a growing interest in the textile sector for more sustainable raw material options, mainly due to the fashion industry's socio-environmental concerns. In order to understand what are the challenges in integrating the most sustainable raw materials in their business, greater dialogue and willingness for cooperation and collaboration between different actors in the sector is needed.

Finally, from the users' point of view, behaviour change is recommended. Seeking information about products' environmental and social impacts, better care and disposal habits, and, mainly, extending the useful life and avoiding exacerbated and unnecessary clothing consumption are some ideas. However, we recognise that advertising plays a crucial role in shaping consumer habits. Consequently, retailers and fashion brands have shared responsibility for consumer awareness and should focus their marketing, communication, and investment efforts on social projects for environmental education.

7 Appendix

List of Selected Life Cycle Assessment Studies of Textiles

#	Year	Title	Site	Fibre*	Reference source
1	2015	Avaliação do ciclo de vida da produção de fios têxteis	Brazil	C	[60]
2	2016	Avaliação do ciclo de vida da produção de algodão no cerrado brasileiro	Brazil	C	[23]
3	2017	Proposta de integração entre ferramentas de avaliação de ciclo de vida do produto e Indústria 4.0 (Industrie 4.0): estudo de caso da indústria têxtil e de confecção brasileira	Brazil	C	[26]
4	2017	Avaliação do ciclo de vida da produção de calça jeans	Brazil	C	[45]

(continued)

(continued)

#	Year	Title	Site	Fibre*	Reference source
5	2015	Iniciativa Compras Sustentáveis & Grandes Eventos: Estudo de pegada de carbono: Camiseta 100% algodão	Brazil	C	[30]
6	2020	Assessment of potential alternatives for improving environmental trouser jeans manufacturing performance in Brazil	Brazil	C	[46]
7	2016	Pegada de carbono de uma calça jeans produzida no Brasil e a influência dos cenários da etapa de uso	Brazil	C	[36]
8	2012	Avaliação do consumo de água e energia durante o ciclo de vida de camisetas de algodão, poliamida e poliéster	Brazil	C, P	[66]
9	2015	Life cycle assessment of cotton textile products in Turkey	Turkey	C	[10]
10	2006	Well dressed? The present and future sustainability of clothing and textiles in the United Kingdom	United Kingdom	C, V	[9]
11	2015	The life cycle of a Jean: Understanding the environmental impact of a pair of Levi's® 501® jeans	USA	C	[39]
12	2019	Environmental impact of textile fibers—what we know and what we don't know	Sweden	C, P, V	[57]
13	2018	Global sustainability report 2018	Global	C, P, V	[18]
14	2017	Increasing textile circulation—consequences and requirements	Finland	C, V	[24]
15	2014	Life Cycle Assessment on cotton and viscose fibers for textile production	USA and China	C, P, V	[25]
16	2019	Environmental impact of cellulose carbamate fibers from chemicallyrecycled cotton	Finland, Germany, Spain, Egypt	C, V	[51]

(continued)

(continued)

#	Year	Title	Site	Fibre*	Reference source
17	2014	Life Cycle Assessment (LCA) of organic cotton—a global average	Global	C	[62]
18	2015	Carbon footprint of textile throughout its life cycle: a case study of Chinese cotton shirts	China	C	[69]
19	2014	LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane	Netherlands	C	[65]
20	2017	Environmental impact of recover cotton in textile industry	Spain	C	[28]
21	2018	Análisis del Ciclo de Vida de un jean producido en Argentina	Argentina	C	[15]
22	2014	Environmental analysis of a cotton yarn supply chain	Egypt, China, India and USA	C	[12]
23	2014	Environmental assessment of coloured fabrics and opportunities for value creation: spin-dyeing versus conventional dyeing of modal fabrics	Europe and Austria	C, P, V	[61]
24	2010	Mistra Future Fashion—review of Life Cycle Assessments of clothing	Global	C, P, V	[21]
25	2010	Environmental impact assessment of man-made cellulose fibres	Asia and Austria	C, P, V	[59]
26	2015	Carbon footprints in the textile industry	Global	C, P, V	[53]
27	2015	Comparative life cycle assessment of natural and man-made textiles	Global	C, P	[47, 48]
28	2015	Environmental impacts of the use phase of the clothing life cycle	Global	C, P	[48]

(continued)

(continued)

#	Year	Title	Site	Fibre*	Reference source
29	2020	Measuring the environmental impact of textiles in practice: calculating the product carbon footprint and life cycle assessment of particular textile products	Global	C	[50]
30	2015	Life cycle assessment of cotton T-shirts in China	China	C	[70]
31	2020	Introduction to sustainability and the textile supply chain and its environmental impact	Global	C, P, V	[49]

* C = cotton, P = polyester, V = viscose
Source Own elaboration

Acknowledgements We are deeply grateful to our project partners Laudes Foundation, Modefica, and Regenerate Fashion, for their great contributions to the Fashion Threads report. We also want to thank Larissa Roviezzo and Melissa O de León, from Regenerate Fashion; Mario Monzoni and Annelise Vendramini, from the Center for Sustainability Studies (FGVces) for improving the quality of this study. Lastly, we thank the team at the Center for Sustainability Studies (FGVces) and Modefica.

References

1. ABIPET (2019) Censo da reciclagem do pet no Brasil: 11ª edição. https://abipet.org.br/wp-content/uploads/2022/02/ABIPET_Infografico_Censo-2019.pdf
2. ABIT (2017) O Setor Têxtil e de Confecção e os Desafios da Sustentabilidade. www.abit.org.br
3. ABIT (2022) Perfil do Setor. Associação Brasileira da Indústria Têxtil e de Confecção. www.abit.org.br
4. ABNT (2014) ABNT NBR ISO 14040: Gestão ambiental – Avaliação do ciclo de vida – Princípios e estrutura. Associação Brasileira de Normas Técnicas, Rio de Janeiro, 2009
5. ABNT (2014) ABNT ISO/TS 14067: Gases de efeito estufa — Pegada de carbono de produtos —Requisitos e orientações sobre quantificação e comunicação. Rio de Janeiro: [s.n.]
6. ABRAFAS (2022) ABRAFAS – Estatísticas. http://www.abrafas.org.br/
7. ABRAPA (2022) Algodão no Brasil. https://www.abrapa.com.br
8. ABRASCO (2015) Dossiê ABRASCO: um alerta sobre os impactos dos agrotóxicos na saúde. EPSJV, Exp ed. Rio de Janeiro, São Paulo
9. Allwood J et al (2006) Well dressed?
10. Baydar G, Ciliz N, Mammadov A (2015) Life cycle assessment of cotton textile products in Turkey. Resour Conserv Recycl 104:213–223
11. BCI (2022) Where is better cotton grown?—Brazil. https://bettercotton.org/where-is-better-cotton-grown/brazil
12. Bevilacqua M et al (2014) Environmental analysis of a cotton yarn supply Chain. J Clean Prod 82:154–165

13. BNDES (2014) Setor de fibras sintéticas e suprimento de intermediários petroquímicos. Rio de Janeiro
14. Bombardi LM (2017) Geografia do uso de agrotóxicos no Brasil e conexões com a União Europeia. FFLCH-US ed. São Paulo
15. Bongiovanni RG, Tuninetti L (2018) Análisis del Ciclo de Vida de un jean producido en Argentina. LALCA - Revista Latino-Americana em Avaliação do Ciclo de Vida 2(1):9–34
16. Bracell (2020) Bracell. https://www.bracell.com
17. Brasil (2020) Comex Stat: Comex Vis. http://comexstat.mdic.gov.br/pt/comex-vis
18. C&A (2018) Global sustainability report 2018. https://sustainability.c-and-a.com/uk/en/sustainability-report/fileadmin/pdf-sustainability/generate/globalsustainabilityreport2018/en/globalsustainabilityreport2018-en.pdf
19. Carvalho SL (2004) Eutrofização Artificial: Um problema em rios lagos e represas
20. Changing Markets Foundation (2017) Roadmap towards responsible viscose & modal fibre manufacturing
21. Chapman A (2010) Mistra future fashion—review of life cycle assessments of clothing, no July, p 32
22. CONAB (2022) Série histórica das safras. https://www.conab.gov.br/info-agro/safras/grãos
23. Costa KR et al (2016) Avaliação do ciclo de vida da produção de algodão no cerrado brasileiro. V Congresso Brasileiro em Gestão do Ciclo de Vida. Anais
24. Dahlbo H et al (2017) Increasing textile circulation—consequences and requirements. Sustain Prod Consum 9(July 2016):44–57
25. Dibdiakova J, Timmermann V (2014) Life cycle assessment on cotton and viscose fibres for textile production. Innovation application of regenerated wood cellulose fibre. Anais. http://www.costfp1205.com/en/events/Documents/BangorWS/Dibdiakova.pdf
26. Duarte A (2017) Proposta de integração entre ferramentas de avaliação de ciclo de vida do produto e Indústria 4.0 (Industrie 4.0): estudo de caso da indústria têxtil e de confecção. [s.l.] Universidade Estadual de Campinas
27. Ellen Macarthur Foundation (2017) A new textiles economy: redesigning fashion's future. Ellen MacArthur Foundation. https://www.ellenmacarthurfoundation.org/publications/a-new-textiles-economy-redesigning-fashions-future
28. Esteve-Turrillas FA, De La Guardia M (2017) Environmental impact of recover cotton in textile industry. Resour Conserv Recycl 116:107–115
29. Fontes S (2019) China é fundamental na celulose. https://valor.globo.com/empresas/noticia/2019/10/24/china-e-fundamental-na-celulose-diz-poyry.ghtml
30. Giasson F et al (2015) Estudo da Pegada de Carbono: Camiseta 100% Algodão. In: Iniciativa Compras Sustentáveis & Grandes Eventos. MMA, PNUMA, FGVces, São Paulo, p 55
31. Greenpeace (2016) Timeout for fast fashion. Greenpeace, pp 1–7
32. IBGE (1999) Manual Técnico de Uso da Terra. Rio de Janeiro
33. IEMI (2021) Brasil Têxtil 2021: Relatório Setorial da Indústria Têxtil Brasileira. São Paulo
34. IPCC (2014) Glossary. In: Climate change 2014: mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge and New York, pp 6–8
35. ISO (2014) ISO 14046: environmental management—water footprint—principles, requirements and guidelines. Switzerland
36. Joner S et al (2016) Pegada de carbono de uma calá jeans produzida no Brasil e a influência dos cenários da etapa de uso. V Congresso Brasileiro em Gestão do Ciclo de Vida. Anais...Fortaleza
37. Kiss B, Dinato R, Fernandes, M (2016) Experiências e reflexões sobre a gestão do ciclo de vida de produtos nas empresas brasileiras. 1a edição ed. São Paulo
38. Legnaioli S (2020) Impactos ambientais das fibras têxteis e alternativas. https://www.ecycle.com.br/5810-impacto-ambiental-das-roupas.html
39. Levi Strauss & Co. The life cycle of a jean. Understanding the environmental impact of a pair of Levi's 501 jeans. http://levistrauss.com/wp-content/uploads/2015/03/Full-LCA-Results-Deck-FINAL.pdf

40. Mendes Junior BDO (2021) Setor têxtil. Caderno Setorial ETENE - Banco do Nordeste 185:1–10. https://www.bnb.gov.br/s482-dspace/bitstream/123456789/954/3/2021_CDS_185.pdf
41. Modefica (2017) 4 Razões Para Você Pensar Duas Vezes Antes de Optar Pela Viscose. https://www.modefica.com.br/4-razoes-viscose-roupa-insustentavel/#.XzLtiijD_IV
42. Modefica (2019) Algodão Orgânico no Brasil: MST, Agroecologia e Justiça Social. https://www.modefica.com.br/algodao-organico-mst-justica-social/#.Xz7GVchKjIU
43. Modefica (2020) Possibilidades para Moda Circular no Brasil: Padrões de consumo, uso e descarte de roupas. https://reports.modefica.com.br/pesquisa-consumo-uso-descarte
44. Modefica, FGVces, Regenerate (2020) Fashion threads: systemic perspectives for a circular fashion. São Paulo. https://reports.modefica.com.br/fashion-threads/
45. Morita AM et al (2017) Avaliação do Ciclo de Vida da produção de calça jeans. In: 6th International workshop advances in cleaner production. Anais...São Paulo
46. Morita AM et al (2020) Assessment of potential alternatives for improving environmental trouser jeans manufacturing performance in Brazil. J Clean Prod 247
47. Muthu SS (2015) Comparative life cycle assessment of natural and man-made textiles. In: Handbook of life cycle assessment (LCA) of textiles and clothing. Elsevier Ltd., Hong Kong, pp 275–281
48. Muthu SS (2015) Environmental impacts of the use phase of the clothing life cycle. In: Handbook of life cycle assessment (LCA) of textiles and clothing. Elsevier Ltd., Hong Kong, pp 93–102
49. Muthu SS (2020) Introduction to sustainability and the textile supply chain and its environmental impact. In: Assessing the environmental impact of textiles and the clothing supply chain. [s.l.] Elsevier Ltd., pp 1–32
50. Muthu SS (2020) Measuring the environmental impact of textiles in practice. In: Assessing the environmental impact of textiles and the clothing supply chain. [s.l.] Elsevier Ltd., pp 161–179
51. Paunonen S et al (2019) Environmental impact of cellulose carbamate fibers from chemically recycled cotton. J Clean Prod 222:871–881
52. Periyasamy AP, Wiener J, Militky J (2017) Life-cycle assessment of denim. [s.l.] Elsevier Ltd
53. Peters G et al (2015) Carbon footprints in the textile industry. In: Handbook of life cycle assessment (LCA) of textiles and clothing. [s.l.] Elsevier Ltd., pp 3–30
54. Quantis (2018) Measuring fashion
55. Regenerate Fashion (2020) Moda Circular, Reciclagem Têxtil e Cenários circulares para fibras têxteis no Brasil. Regenerate Fashion LCC, p 62
56. Sandin G, Peters GM (2018) Environmental impact of textile reuse and recycling—a review. J Clean Prod 184:353–365
57. Sandin G, Roos S, Johansson M (2019) Environmental impact of textile fibers—what we know and what we don’t know. Goteborg [s.n.]
58. Shen L, Patel MK (2010) Life cycle assessment of man-made cellulose fibres. Lenzinger Berichte 88(88):1–59
59. Shen L, Worrell E, Patel MK (2010) Environmental impact assessment of man-made cellulose fibres. Resour Conserv Recycl 55(2):260–274
60. Silva TL et al (2015) Avaliação do ciclo de vida da produção de fios têxteis. Revista Química Têxtil 119:28–43
61. Terinte N et al (2014) Environmental assessment of coloured fabrics and opportunities for value creation: spin-dyeing versus conventional dyeing of modal fabrics. J Clean Prod 72:127–138
62. Textile Exchange (2014) Life cycle assessment (LCA) of organic cotton. Echterdingen
63. Textile Exchange. 2019 preferred fiber and materials market report
64. Thomas B et al (2012) A carbon footprint for UK clothing and opportunities for savings—final report
65. Van Der Velden NM, Patel MK, Vogtländer JG (2014) LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane. Int J Life Cycle Assess 19(2):331–356
66. Vasconcelos FB et al (2012) Avaliação do consumo de água e energia durante o ciclo de vida de camisetas de algodão, poliamida e poliéster. Revista Química Têxtil, n 1979

67. Velloso Sarmento Gomes A, Róblis Versiani Costa N, Della Santina Mohallem N (2016) Os Tecidos e a Nanotecnologia. Química Nova na Escola 34(4):288–296
68. Vidal A (2013) O renascimento de um mercado: o setor de celulose solúvel. BNDES Setorial 38:79–130
69. Wang C et al (2015) Carbon footprint of textile throughout its life cycle: a case study of Chinese cotton shirts. J Clean Prod 108:464–475
70. Zhang Y et al (2015) Life cycle assessment of cotton T-shirts in China. Int J Life Cycle Assess 20(7):994–1004

The Role of Life Cycle Assessment in Analyzing Circular Economy Strategies in the Clothing Sector: A Review

Lorena Lizarzaburu-Egüez, Susana Toboso-Chavero, and Martí Rufí-Salís

Abstract Clothes play a main role in societies. They protect people from weather conditions and are important means of communication and expression. However, the clothing industry is at the center of increasing criticism because of its contribution to climate change, resource depletion, water pollution, and waste generation, among others. These impacts are closely linked to the fast-paced, massive consumption-oriented, and linear model in which clothes are produced, marketed, distributed, used, and disposed of. The Circular Economy (CE) concept emerged as an alternative to the mainstream linear scheme, which seeks to recycle wastes into resources, keep products, components, and materials at their highest level of utility and value for as long as possible, while designing out waste and pollution and regenerating natural systems. Despite some identified challenges, Life Cycle Assessment (LCA) is very well suited to analyze CE strategies and contribute to a better environmental performance of products and systems. In this context, this research aims to contribute to a better understanding of the role of LCA in supporting CE strategies for the clothing industry by conducting a systematic literature review. After analyzing 256 papers, the results show that LCA has been applied to assess the environmental impacts of clothing since 1997, while CE and clothing publications start to appear almost 20 years later. Despite the CE framework being newer than the LCA, the speed in which CE publications increase is significantly faster. There is a wide range of LCA studies applied to different clothing life cycle stages that could be used to inform CE strategies. A number of these studies were specifically developed to inform CE. Our review shows that CE researchers today are mostly evaluating stakeholder perceptions and consumer attitudes, influenced by a business model mindset. However, CE strategies require a conscious analysis to be proved efficient and claiming that currently promoted generic circular fashion strategies have

L. Lizarzaburu-Egüez · S. Toboso-Chavero · M. Rufí-Salís (✉)
Sostenipra Research Group (SGR 01412), Institute of Environmental Sciences and Technology (CEX2019-000940-M), Z Building, Universitat Autònoma de Barcelona (UAB), Campus UAB, 08193 Bellaterra, Barcelona, Spain
e-mail: marti.rufi@uab.cat

S. Toboso-Chavero
e-mail: susana.toboso@uab.cat

S. S. Muthu (ed.), *Progress on Life Cycle Assessment in Textiles and Clothing*,
Textile Science and Clothing Technology,
https://doi.org/10.1007/978-981-19-9634-4_4

better environmental performance than traditional strategies in any scenario would still be inexact. Therefore, further work in landing CE strategies through a closer relationship with science-based tools like LCA is needed.

Keywords Life cycle assessment · Circular economy · Clothing · Sustainability · Circularity · Literature review · Environmental assessment

1 Introduction

In addition to protecting people from weather conditions, clothes are important means of communication and expression and therefore play a major role in societies. Today, mainstream clothing consumption is characterized by a "fast fashion" model, which intends to respond quickly to changes in fashion trends and promotes high consumption rates through rapid obsolescence [9, 44, 58, 100, 163, 165]. It is estimated that, today, major apparel brands target to complete design, production, and sales cycles in one month on average; and get to roll out between 14 to 16 collections each year [9]. In the last 20 years, this dynamic has led to a 400% increase in global clothing consumption, reaching 800 billion new items purchased annually [19, 80, 161].

Although a significant contributor to the global economy, the garment industry is at the center of increasing criticism due to its extensive social and environmental costs. The clothing industry contributes to global warming by emitting 1.2 billion tons of greenhouse gas (GHG), which exceeds international flights and maritime shipping combined [19]. If these emissions are not reduced, it is projected that the industry could use up to 25% of the global carbon budget by 2050 [105]. Also, the industry consumes 1.5 trillion liters of water per year and is responsible for around 20% of total industrial water pollution and 35% of the microplastic pollution [52, 147]. It produces more than 92 million tons of waste per year, that mostly ends up in landfill or burnt [27, 100]. In this context, there is an urgent need to rethink clothing systems to enhance a model that can be sustained in the long term.

Like most industries, the clothing industry is mainly based on a linear and inefficient model of extracting, producing, using, and disposing [13, 40, 100]. An alternative to advance toward more sustainable production and consumption patterns is to implement strategies to keep products, components, and materials at their highest level of utility and value for as long as possible; to design out waste and pollution, and to regenerate natural systems [39]. These strategies are the main components of the Circular Economy (CE) concept [39], which has gained momentum in recent years as a response to the current environmental crisis [110].

In the following sections of the chapter, we will cover how the apparel industry has increased its attention toward CE practices (Sect. 1.1) and how Life Cycle Assessment (LCA) is positioned as a tool to assess the environmental performance of clothing products (Sect. 1.2). After describing the goal of the chapter (Sect. 1.3) and the methodology followed (Sect. 2), the first part of the results and discussion part of the chapter (Sect. 3), is divided between the groups of words used to perform the literature review (Sect. 3.1, 3.2, and 3.3). Section 3.4 explores the connections between LCA and CE in the clothing sector from an LCA practitioner's, a CE researcher's, and a designer's perspective. The chapter is finally closed with the conclusions.

1.1 Circular Economy (CE) for a More Sustainable Apparel Industry

The CE concept has evolved as a new sustainability paradigm focused on reducing, reusing, recycling, and recovering materials in production, distribution, and consumption processes [70]. The CE can be applied at micro, meso, and macro levels [33], and has the potential to improve the environmental performance of products, services, companies, industries, cities, regions, and beyond [33]. CE Strategies are categorized under five functions, which have been termed "take", "make", "distribute", "use", and "recover" [124]. These functions aim to take into consideration the entire life cycle of products and services. Knowing the environmental impacts related to each stage of the clothing life cycle aids to prioritize circular strategies.

The list of circular strategies may be comprehensive and can vary depending on the product or service. Prieto-Sandoval [115] propose thirteen general action points for CE implementation. For the take function, the authors recommend to stop using toxic and non-sustainable materials, selecting raw materials and suppliers based on their environmental performance, using fully recoverable materials, and ensuring process and product transparency. For the make function, they recommend educating employees on sustainability issues, executing resource optimization, using sustainable energy sources, and adopting eco-design and zero waste production processes. For the distribute function, the authors propose optimizing stocks, routes, and space for both forward and reverse logistics; and collaborating with stakeholders for commitment. For the use function, the recommendation includes communicating the green attributes of products and adopting green marketing strategies, market segmentation, and product system. And finally, the recovery function's recommendation includes the implementation of effective and efficient reuse and recycle systems.

Despite there being other actions to reach a circular clothing industry [11], the actions presented by Prieto-Sandoval [115] serve as a good start. Actions are easy to name, but their successful implementation still face barriers, and depends on several factors. These factors are related to public policy, market conditions, available technology, economical resources, capabilities, and competencies [115, 124].

1.2 Life Cycle Assessment (LCA) to Assess the Environmental Performance of Clothing Products

The viability of CE strategies is key for a sustainable garment industry; thus, Life Cycle Assessment (LCA) might be an appropriate tool to measure them. LCA is a quantitative tool applied to analyze the environmental impacts of products, processes, and services from cradle to grave stages. LCA is a four-step process, namely goal and scope definition, life cycle inventory, life cycle impact assessment, and life cycle interpretation. Different environmental impact indicators such as carbon footprint, water footprint, eutrophication, acidification, and human toxicity can be measured [45]. The complexity of the lengthy supply chain in clothing products, lack of data unavailability, and deficient know-how has already been identified as some of the barriers to conducting an LCA study of a clothing product [94]. Nevertheless, despite the challenges, LCA is still well suited to inform CE strategies.

The life cycle of clothing products consists of several key stages: raw material extraction, fabric manufacturing, clothing manufacturing, retailing, use, end-of-life, and transportation [41, 93, 103]:

(a) Raw material extraction. Clothing pieces can be composed of one or more combined raw materials, that can be natural or manufactured. Natural fibers include animal and vegetable fibers and manufactured fibers include synthetic, regenerated cellulosic, inorganic, and recycled fibers [93]. The extraction processes are varied, depending on the raw material. For example, cotton production starts with agricultural cultivation, which is water and chemical demanding [18, 43, 93]. Polyester manufacturing is produced using petrochemical [112, 134, 158], which involves energy consumption and chemicals [22].

(b) Fabric manufacturing. Fabrics are manufactured either through nonwoven, weaving, or knitting processes. The woven and knitted fabric manufacturing stage can be divided into two sub-stages: yarn manufacturing and fabric manufacturing. Yarn manufacturing involves spinning, and in some cases yarn dyeing, before the fabric production. Knitting and weaving processes involve a substantial amount of energy and generate solid wastes while yarn and fabric dyeing involve high water intake, chemical intake, and wastewater output [48, 58, 129, 131].

(c) Clothing manufacturing. This stage includes fabric cutting, sewing, and assembly, followed by value-adding activities like ironing and packaging [41, 49]. These activities are highly labor-intensive processes and energy is generally the main input in this stage. Garments may also be dyed, which requires the substantial use of water and chemicals [41, 48, 95].

(d) Use. This is considered the most critical and variable stage in the life cycle of clothing because of the important amount of energy and water used for washing, drying, ironing, and dry cleaning [35, 38, 48, 162].

(e) End-of-life. This stage may pose major environmental impacts depending on the disposal method [61]. End-of-life reuse, recycling, and incineration are commonly used waste as alternatives to landfilling [111]. Reuse represents the best management strategy followed by recycling as reusing since it does not involve further processing of materials [16, 32, 46, 76]. Incineration and gasification are used as energy recovery strategies but have a worse environmental performance than resource recovery methods. Landfilling is generally considered to have the worst environmental impact as it is associated with greenhouse gases (GHG) emissions and soil and water pollution [48].

(f) Transportation. Transportation occurs along every stage of the clothing life cycle [146]. Air freight is considered the worst option because of its substantial contribution to GHG emissions and climate change [41].

1.3 Goal of the Review

The goal of this review is to evaluate the current literature on CE and LCA to understand how these two frameworks have been applied in context of the clothing industry and identify convergence points or gaps. It could be assumed that being a comprehensive method to measure the environmental impacts of products, and services, LCA would be extensively applied to support CE claims. However, no previous work was identified to confirm this hypothesis. Our specific research questions include:

- Is there a temporal trend in clothing-focused publications on LCA and CE?
- Is there a geographic trend in clothing-focused publications on LCA and CE?
- What are the types of clothing-focused publications on LCA and CE?
- How many publications on LCA and clothing are framed inside the CE concept?
- Which is the methodologic approach applied in publications on LCA and CE focusing on clothing?
- Which functions, functional units, limits, and indicators are applied in LCA and clothing publications?
- Which stage of the clothing life cycle is included in the revised publications?

2 Methodology

We conducted a systematic review of scientific literature, which is a rigorous method applied to obtain credible outcomes for specific research questions. The review was conducted following the PRISMA method, which is detailed and presented in an external document available under request to the corresponding author. The research was conducted from February to August 2022, using the online databases Scopus and Web of Science (WOS). Keywords were applied in three groups. The first group included the combination of "LCA", "Life cycle assessment", "clothing", "fashion", and "apparel" keywords. The second group included the combination of "circular economy", "fashion", and "apparel" keywords. Finally, the third group included the combination of "circular economy and LCA" and "clothing", "fashion", and "apparel" keywords.

Table 1 Preliminary research results

Group	Specific keywords	Number of papers
1	"LCA", "Life cycle assessment", "clothing", "fashion", and "apparel"	73
2	"circular economy", "fashion", and "apparel"	175
3	of "circular economy and LCA" and "clothing", "fashion", and "apparel"	1

All types of academic publications were included and no geographical or publication year scoping was applied. A keyword search was configured to include abstracts, keywords, and titles in the Scopus database, while the basic search "topic" was applied in WOS. After searching, the title and keywords were screened, and publications that were not related to LCA, clothing, apparel, or fashion, were excluded. A second screening was conducted after reading the abstracts, and publications related to protective equipment, social scopes, workwear, accessories, and shoes were excluded. After the elimination of duplicated publications, full documents were screened and those not reporting on clothing products were excluded. The eligible documents were analyzed based on the research questions and internally stored. Publications that were not publicly available or were accessible through the Spanish research association (FECYT) and the Universitat Autònoma de Barcelona (UAB) libraries, were excluded. All the steps described in this paragraph were registered in an external document available under request to the corresponding author.

The review incorporates 253 publications, including journal articles, books, book chapters, and conference papers. The list of reviewed publications is documented in the "results table" tab in the supporting information hyperlinked above. The publications were classified based on the three groups of keyword combinations applied (Table 1).

3 Results and Discussions

3.1 Group One. Research Combining "LCA", "Life Cycle Assessment", "Clothing", "Fashion", and "Apparel" Keywords

The application of the first group of keyword combinations "LCA", "Life cycle assessment", "clothing", "fashion", and "apparel", resulted in 385 publications. After applying the filtration criteria explained in the methods section, and shown in Table 2, the number of publications was reduced to 73.

In the end, the 73 publications were stored. No filter was applied regarding the type of publication, and the search yielded original research articles, literature reviews,

Table 2 Initial research and filtration processes for keyword combination group 1

Keyword X	Keyword Y	Database	Papers identified	Title and keyword screening	Abstract screening	Duplicates elimination	Full text screening	Mendelay storage
			Records identified through database searching	Records after tittle and keyword screening (n-) for excluding obvious errors	Records after abstract screening (n-)	Number of papers with full text available after duplicates removed	Records after full text check	Number of papers with full text available stored in Mendelay
“LCA”	AND “clothing”	Scopus	78	55	49	49	44	38
“LCA”	AND “clothing”	WOS	50	40	34	7	6	6
“LCA”	AND “apparel”	Scopus	38	33	33	28	27	22
“LCA”	AND “apparel”	WOS	30	27	25	1	1	1
“Life cycle asssesment”	AND “clothing”	Scopus	0	0	0	0	0	0
“Life cycle asssesment”	AND “clothing”	WOS	0	0	0	0	0	0
“Life cycle asssesment”	AND “apparel”	Scopus	0	0	0	0	0	0
“Life cycle asssesment”	AND “apparel”	WOS	0	0	0	0	0	0
“LCA”	AND “fashion”	Scopus	107	48	16	4	4	4
“LCA”	AND “fashion”	WOS	82	16	14	6	4	2
		Total	385	219	171	95	86	73

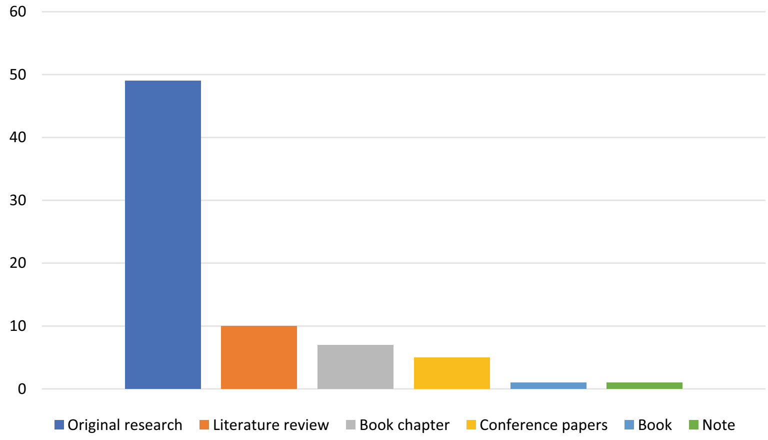


Fig. 1 Type of publications for keyword combination group 1

books, book chapters, conference papers, and notes. Compared to other types of publications, the number of publications presenting original research work was significant. To be specific, from the final list of 73 publications, 50 were original research articles, 10 were literature reviews, seven were book chapters, four were conference papers, one was a book, and one was a note (see Fig. 1).

3.1.1 LCA and Clothing in Time

Results date from 1997 to 2022, which represents a time frame of 25 years (see Figs. 2 and 3). 2021 is the year with the higher number of publications, with a total of nine original research papers and four literature reviews. In 2020, there were 10 original research papers, and a conference paper published. In 2015, there were seven original research papers, one book, and seven chapters published. It is worthy of mention that all the chapters are part of the same book.

The first publication in 1997 [56] coincides with an important milestone in LCA history, through the release of the ISO 14040 standard on LCA principles and framework [10]. This was followed by the release of the ISO 14041 standard on goal and scope in 1998, the release of ISO 14042 standard on life cycle impact assessment, and the ISO 14043 standard on life cycle interpretation in 2000. LCA kept evolving [10] with the release of Ecoinvent database version 1.0 in 2003, and the establishment of a general methodological framework and guidelines through ISO 14040 and ISO 14044, in 2006 [63, 64].

The evolution of LCA can be noticed in the reviewed papers, and the execution of the methodology in accordance with the ISO 14040 and 14,044 starts to appear in publications from 2014, and onward [7, 16, 89–91, 106, 107, 117, 143, 154, 155, 160, 163]. The evolution of the LCA seems to have a direct influence on the number and frequency of original research publications. In 1997, 2003, and 2006 (a time

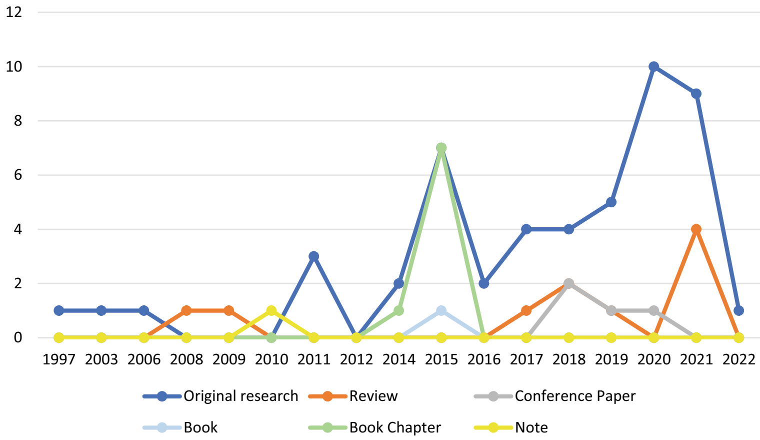


Fig. 2 Type of publications for keyword combination group 1, by year

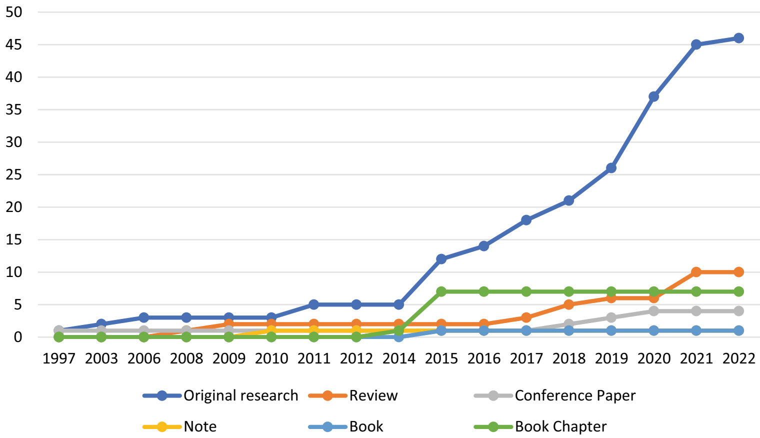


Fig. 3 Type of publications for keyword combination group 1, by year—accumulated

period of 11 years) there were only three papers published [56, 99, 157]. Five years later, in 2011 there were three papers published [87, 152, 159]. After 2014, at least two papers were published each year until 2021 [8, 75, 79, 95, 111, 122, 137, 143].

3.1.2 Geographical Scopes

From the reviewed publications, 10 have a worldwide scope and seven study the European region as a block. The other publications study one or several specific countries. The most studied country is Sweden, with 10 mentions, followed by USA, with nine mentions, and China with six mentions. While Germany, Italy, and Japan were at the center of five publications, UK and Australia are the focus in four and three publications, respectively. Finland, Norway, and Switzerland are studied twice. Finally, Portugal, Denmark, Iceland, New Zealand, Mexico, Vietnam, Austria, Netherlands, Estonia, France, Turkey, Poland, and Hong Kong are studied once each.

Worldwide scope publications correspond to literature reviews. The latest reviews were published in 2021. This review, written by [93], focuses on collating data regarding life cycle inventories (LCI) of clothing, and then provides LCI data on energy use, water use, and GHG for a range of materials at each life cycle stage. Their analysis shows that raw material extraction usually has the highest environmental impact, while flax and recycled cotton are the fibers with less environmental impact. Another review, written by [128], aims to study the application of LCA in laundry wastewater treatment. Despite few references including an LCA, the authors were able to conclude that the main environmental hazard in laundry wastewater is electricity consumption.

Luo et al. [82] present the methods that can be used to measure the environmental sustainability of textile products, including life cycle assessment, environmental footprint, eco-efficiency, and the Higg index. The authors find relatively limited cases for the first three -generic- methods. They relate the limited application of these methods to challenges regarding the length and complexity of the production and consumption processes and value chains in clothing. Similarly, Gonçalves and Silva [55] review the methodologies and criteria of sustainability applied to fashion products. However, their review shows that the most common key performance indicator (KPI) is the global warming impact (expressed as CO_2 eq) based on LCA principles, which they say, provides an appropriate base to monitor and benchmark products.

Watson and Wiedeman [153] study the methodological choices in LCA-based apparel rating tools and issue recommendations for the assessment of fabrics made from natural fibers. Laitala et al. [73] and Laitla et al. [74] review the environmental impacts of clothing at the use stage. While the first authors study different fiber types, the second authors focus on wool apparel. Sandin [125] concentrated on the environmental impact of textile reuse and recycling. Shen and Patel [133] review LCA studies in order to gain insight into the environmental profiles of polysaccharide products (e.g., viscose or natural fiber polymer composites) in comparison with their conventional counterparts (e.g., cotton or petrochemical polymers) (Fig. 4 and Table 3).

The high amount of LCA focused on Sweden is mainly related to a group of researchers that were active on this subject from 2015 and 2019 (see Table 4). Peter (2019; 2016; 2015; 2015; 2017) was an author of five papers. Sandin (2015; 2016; 2017; 2019) was an author of four papers. Zamani (2015, 2016, 2017) was an author of three papers.

3.1.3 Top Scientific Journals

Journal articles, including original research and reviews, are published in 26 different journals. The top three publishers are the *Journal of Cleaner Production (Elsevier)*

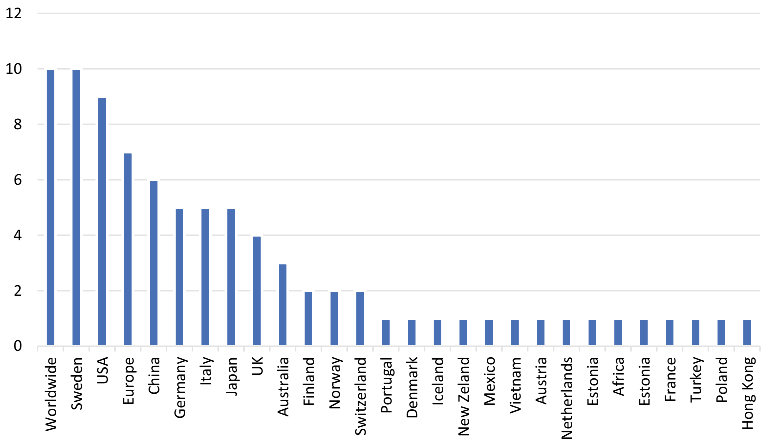


Fig. 4 Geographical scope for group 1 keyword combination

Table 3 Clothing LCA studies in Sweden

Title	Authors	Year
Environmental benefits from reusing clothes	Farrant et al.	2010 [46]
Using the planetary boundaries framework for setting impact-reduction targets in LCA contexts	Sandin et al.	2015 [126]
A Carbon Footprint of Textile Recycling: A Case Study in Sweden	Zamani et al.	2015 [164]
A life cycle assessment (LCA)-based approach to guiding an industry sector toward sustainability: the case of the Swedish apparel sector	Roos et al.	2016 [122]
Life cycle assessment of clothing libraries: can collaborative consumption reduce the environmental impact of fast fashion?	Zamani et al.	2017 [163]
Application of Markov chain for LCA: a study on the clothes 'reuse' in Nordic countries	Paras and Pal	2018
Environmental Prospects for Mixed Textile Recycling in Sweden	Peters et al.	2019 [111]
The environmental impacts of clothing: Evidence from United States and three European countries	Sohn et al.	2021 [137]
Product-service systems and sustainability: Analyzing the environmental impacts of rental clothing	Johnson and Plepys	2021 [67]
Environmental and social performance of valorizing waste wool for sweater production	Martin and Herlaar	2021 [86]

Table 4 Top six journals for group one keyword combination papers

Publication source	Number of papers
Journal of Cleaner Production	12
Sustainability	10
International Journal of Life Cycle Assessment	9
Resources, Conservation and Recycling	5
Journal of Industrial Ecology	3
Sustainable Production and Consumption	2

with 12 publications, *Sustainability (MDPI)* with 10 publications, and the *International Journal of Life Cycle Assessment (Springer)* with nine publications. Other journals, including *Resources, Conservation and Recycling,* the *Journal of cleaner production,* and *Sustainable Production and Consumption* (all three from *Elsevier*), published five, three, and two papers. Finally, the rest of the journals published one paper each.

3.1.4 Types of Products Studied

Functional and functional units are unique for every research, and no trend was identified. Products in functional units include viscose fiber garments, jeans, dresses, pants, shirts, trousers, socks, sweaters, leggings, and jackets. Each paper studies one or more of these products (see Table 5). There is a significant number of publications that are focused on the assessment of t-shirts. To be exact, 13 papers study the environmental impacts of t-shirts. Sweaters are studied in four papers. Jeans, dresses, and jackets are studied in three papers. Trousers and socks are studied in two papers; and viscose fiber garments, pants, leggings, shirts, and shorts are studied in one paper each (Table 6).

3.1.5 Impact Categories

The clothing industry is considered one of the most polluting industries in the world [123]. The processes with the potential to contribute to the unsustainability of the industry include the use of toxic chemicals, water consumption, energy consumption, waste generation, air emissions, transportation, and packaging materials [123, 135]. Textile processing uses as many as 2000 different chemicals [123]. These chemicals either evaporate into the atmosphere, are dissolved in the water that is later discarded into the environment, or are retained in the fabrics, posing a threat to humans and the environment. The clothing industry is one of the highest consumers and polluters of clean water in the world [37]. A single cotton t-shirt requires around 3000 L of water

Table 5 Papers per clothing product

T-Shirts	[8, 30, 46, 75, 77, 84, 89, 90, 122, 130, 137, 152, 159]
Sweater	[16, 86, 154, 155]
Jeans	[122, 130, 137]
Dresses	[67, 122, 160]
Jackets	[16, 90, 122]
Trousers	[46, 75]
Socks	[60, 87]
Viscose fiber garment	[117]
Pants	[30]
Leggings	[30]
Shirts	[30]
Shorts	[75]

to be manufactured, including the amount of water required to grow the cotton and the amount of water used in the wet finishing process [123]. The wet finishing process for dyeing consumes water to convey chemicals first and to wash them out later. In traditional textile production, one ton of fabric could pollute up to 200 tons of water [47]. In addition to chemicals, microplastics are released to wastewater during every washing cycle, and today clothing use is responsible for 35% of global microplastic pollution [52, 147].

The consumption of energy in the clothing life cycle is major and inefficient [96]. The most consuming processes during the production are weaving, knitting, and spinning [48, 58, 129, 131]. However, along the life cycle of clothing, the most worrying stage is the use stage, because of the important amount of energy and water used for washing, drying, ironing, and dry cleaning [35, 38, 48, 162]. The washing is calculated to be responsible for 80% of the total energy consumption of clothes [135].

Like other industries, the clothing industry generates liquid, solid, and gas waste. The industrial solid wastes from the production include ashes, sludge, cardboard, bale wrapping film, plastic bags, paper cones and tubes, and waste fabrics, yarns, and fibers [123]. Also, the industry is responsible for the generation of packaging waste, which can include plastic, paper, metal, aluminum, cotton, and hemp, among others. Yet, the greatest contribution to waste production is linked with the fast pace disposal of clothes, which are increasingly designed to be obsolete in short periods of time [9, 44, 58, 100, 163, 165].

The environmental impacts of clothing´s end-of-life have the potential to be major depending on the disposal method [61]. Methods include reuse, recycling, incineration, landfilling, and gasification [16, 32, 46, 76, 111]. Reuse represents the best management strategy followed by recycling [16, 32, 46, 76], while landfilling is

Table 6 Impact categories and number of times included in papers

Impact categories	Number of inclusions
Greenhouse gas emission/climate change/global warming potential	47
Water use	21
Acidification	19
Energy use	15
Land use	14
Resource use: fossil, mineral materials	12
Human toxicity/ Human carcinogenic potential	12
Freshwater Eutrophication	11
Freshwater Ecotoxicity	10
Ozone depletion	10
Human toxicity—no cancer	9
Photochemical ozone formation	9
Marine Eutrophication	8
Ionizing radiation	7
Eutrophication	7
Marine Ecotoxicity	6
Water scarcity footprint	6
Terrestrial acidification	5
Terrestrial ecotoxicity	5
Water ecotoxicity	4
Chemical use	3
Terrestrial eutrophication	3
Particular matter formation	3
Resource use	2
Renewable and non-renewable energy usage	1
Emissions to water	1
Emissions to land	1
Kmol H+	1
Human Health	1
Water degradation footprint	1
Water alkaline footprint	1

generally considered to have the worst environmental impact because of its contribution to GHG emissions, and soil and water pollution [48]. Currently, 73% of produced clothing ends up in landfills or is incinerated [40].

Fossil fuel consumption contributes to climate change due to carbon dioxide emissions. In addition to carbon, along cloth´s life cycle, nitrogen oxides, sulfur oxides, solvents, and volatile hydrocarbons (e.g., alcohols, aldehydes, and organic acids) are emitted [123]. The clothing industry generally contributes to global warming by emitting 1.2 billion tons of GHG, which exceeds international flights and maritime shipping combined [19]. An important contribution of GHG emissions comes from the transportation of products generally produced in low-labor-cost countries and then distributed around the world [123]. Air freight is considered the worst option for transportation in terms of the amount of GHG emitted [41].

The original research reviewed includes a comprehensive list of impact categories (see Table 7). By far, the most studied impact in clothing research is global warming, with 47 mentions. The energy use, fossil consumption, and the impacts on water, human health, and the ozone are also highly studied.

3.1.6 Clothing Life Cycle Stages

LCA is a systematic scientific approach developed to examine the environmental impacts of products and services along their life cycle. It is considered the most comprehensive approach for the assessment of environmental impacts [123], and therefore is very well suited for the analysis of the performance of the clothing industry. The clothing life cycle consists of several stages: raw material extraction, fabric manufacturing, clothing manufacturing, retailing, use, end-of-life, and transportation [41, 93, 103]. Although, none of the reviewed publications specifically matched life cycle stages, from an LCA perspective, and CE functions, LCA results can perfectly be used to inform CE strategies. However, LCA method is context specific and results cannot be generalized.

From all the studies resulting from applying the keyword combination group one, only 11 take into account all the life cycle clothing stages. Some examples include assessment of global warming potential of jeans and t-shirts in four countries: Germany, Poland, Sweden, and the United States [137]; the evaluation of hotspots across the full life cycle of two merino outdoor apparel products: socks and a men's long-sleeved garment [60]; and the comparison of incineration and reuse of cotton products [46].

Sohn et al. [137] discover that the production stage of jeans and t-shirts has the worst environmental performance in Germany, Poland, and Sweden. Also, the use stage poses important impacts, which depend on washing and drying frequency and the carbon intensity of associated energy consumption, that could even exceed the production impacts. Henry et al. [60] show, on the one hand, that in terms of energy demand, the processing of merino garment, and the use phases are the ones with a higher contribution. On the other hand, the use phase has the highest contribution to water use. Farrant et al. [46] conclude that the collection, processing, and transport of second-hand cotton clothing has insignificant environmental impacts compared to the benefits of replacing virgin clothing. The study shows that 14% of global warming and 45% of human toxicity could be reduced by reusing clothes.

Table 7 Initial research and filtration processes for keyword combination group two

Keyword X	Keyword Y	Database	Papers identified	Title and keyword screening	Abstract screening	Duplicates elimination	Full text screening	Mendelay storage
			Records identified through database searching	Records after tittle and keyword screening (n-) for excluding obvious errors	Records after abstract screening (n-)	Number of papers with full text available after duplicates removed	Records after full text check	Number of papers with full text available stored in Mendelay
"Circular economy*"	AND "clothing"	Scopus	127	120	99	96	69	69
"Circular economy*"	AND "clothing"	WOS	93	62	60	24	18	18
"Circular economy*"	AND "apparel"	Scopus	47	47	47	34	18	18
"Circular economy*"	AND "apparel"	WOS	37	37	37	7	7	7
"Circular economy*"	AND "fashion"	Scopus	211	160	71	56	56	52
"Circular economy*"	AND "fashion"	WOS	50	46	46	13	11	11
		Total	565	472	329	232	183	175

3.1.7 Challenges of Applying LCA on Clothing Products

The application of LCA requires the definition of research objectives, the compilation of inputs and outputs, the quantification of resources, and the interpretation of results [82]. Results can be expressed at midpoint and endpoint levels. The midpoint level is comprised of indicators in several categories like climate change, water use, fossil depletion, etc. The endpoint level summarizes indicators into three damage categories: resources, ecosystems, and human health. LCA is data intensive and requires the collection of data inventory items involved in the product life cycle. Collecting in-field data is the most accurate approach but takes a lot of time and labor [154], and the availability of data in research papers is specific and limited [82].

Luo et al. [82] and Barnes et al. [7] discuss the challenges of applying the LCA method specifically to clothing products. These products pose a unique challenge for LCA practitioners, due to long and unstandardized production and consumption processes, which can make data collation highly difficult [82]. The variety of products and the pace at which these products evolve are greater and faster compared to other industries [68]. Fast fashion brands provide more than 20 new collections each year [120], and in this context data collection for this kind of companies is daunting. The clothing industry's value chain is distributed globally, and data consistency is difficult [82]. Data is not necessarily interchangeable due to, for example, significant technical differences in different regions [7]. Coinciding with the results of the current research, Luo et al. [82] identify that most LCA studies illustrate simple product types like cotton shirts and t-shirts, and conclude that data from publications is limited.

3.2 Group Two. Research Combining "Circular Economy", "Clothing", "Fashion", and "Apparel" Keywords

The application of the second group of keyword combinations "circular economy", "clothing", "fashion", and "apparel", resulted in 565 publications. After applying the filtration criteria explained in the methods section and shown in Table 2, the number of publications was reduced to 175 (Table 7).

In the end, the 175 publications were stored. No filter was applied regarding the type of publication, and the search yielded original research articles, literature reviews, book chapters, and conference papers. Compared to other types of publications, the number of publications presenting original research work was significant, similar to combination keywords group one. From the final list of 175 publications, 118 were original research articles, 23 were literature reviews, 11 were book chapters, and 23 were conference papers (see Fig. 5).

Out of 118, more than 30% of the original research papers were quantitative. A group of these papers, 13%, study consumer attitudes toward circular fashion [17, 29, 50, 83, 150]. Vehmas et al. [150] assure that the transition toward a circular economy requires fundamental behavior changes and examine attitudes toward low fashion,

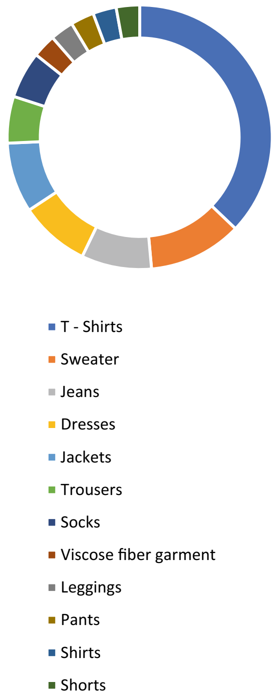


Fig. 5 Products studied in group 1 keyword combination papers

swapping, clothes rent, and other new circular clothing strategies. The results show low awareness of these models but a strong willingness to engage. Machado et al. [83] aim to understand the role of consumers´ motivations in the context of the CE through the reuse of clothes and discover that economic, critical, and hedonic motivations are overlapping and fundamental drivers of second-hand items. Gazzola et al. [50] study the perception of new generation of consumers and discover strong interest. Castro-López et al. [17] confirm consumer orientation toward circular fashion. However, Das et al. [29] analyze why customers keep returning to fast fashion and what is holding them back from buying sustainable fashion. Lack of understandable and clear information, the price or available budget, and the importance of social influence appear as the main obstacles.

3.2.1 CE and Clothing in Time

Results date from 2016 to 2022, which represents a time frame of six years (see Figs. 6 and 7). 2021 is the year with the higher number of publications. There are 51 publications: 32 original research papers, 12 literature reviews, five conference papers, and two book chapters. In 2020, there is total of 40 publications: 29 original research papers, six literature reviews, five conference papers, and two book chapters.

In 2019 there are 31 publications, in 2018 there are 14, in 2017 there are 10, and in 2016 there are two.

The CE concept has been receiving increasing attention during the last 10 years [119] s, as the urgency of closing material loops has been actively promoted by global key actors such as the OECD, the WEF, and the UNEP. Compared to LCA, the CE concept is a newer approach in the discussion of clothing sustainability, and publications combining CE and clothing start appearing almost 20 years later than

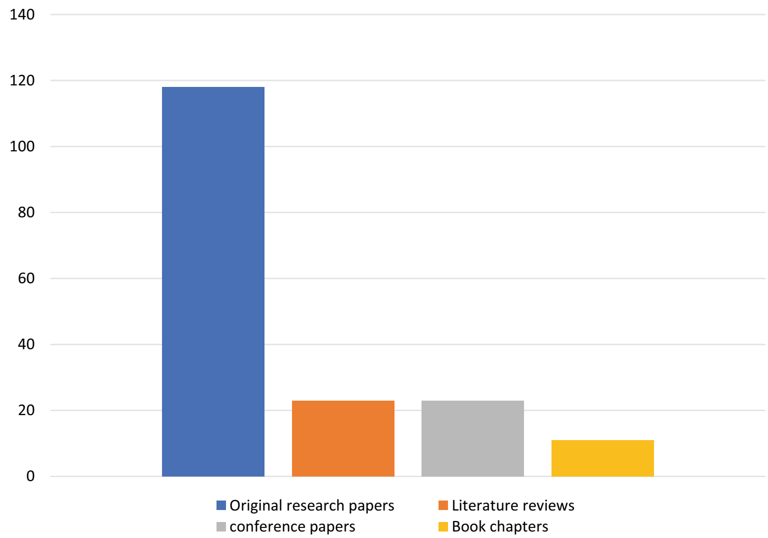


Fig. 6 Type of publications for keyword combination group 2

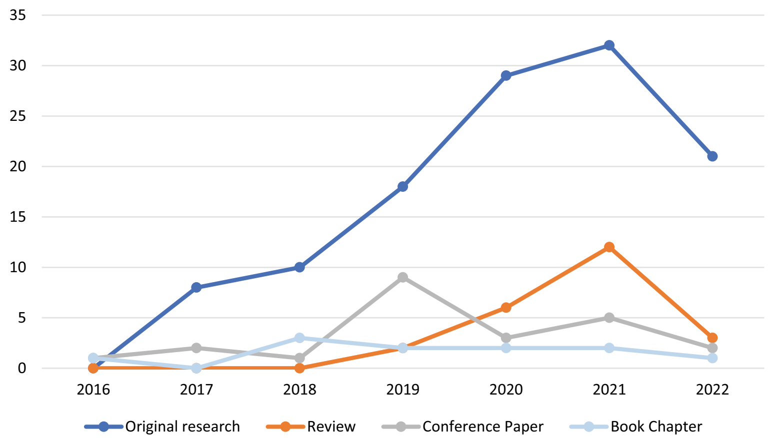


Fig. 7 Type of publications for keyword combination group 2, by year

the publication on LCA and clothing. However, the pace at which CE publications increase is greater. For instance, original research went from zero to eight in the first year—from 2016 to 2017, from eight to ten in the second year—from 2017 to 2018, from ten to eighteen in the third year—from 2018 to 2019, from eighteen to twenty-nine in the fourth year—from 2019 to 2020, and from twenty-nine to thirty-two in the last year—from 2020 to 2021.

In 2021, there is an interesting number of literature reviews. Aguiar et al. [1] review the drivers, barriers, and practices influencing the implementation of CE initiatives in fashion. Stenton et al. [139, 140] interconnect design, science, and industry to explore how textiles can be created from food industry waste, including hemp, pineapple, banana, cane, rice, grape, and potato waste. Authors support the development of producing novel, eco-friendly materials, but also highlight a gap in the literature surrounding the assessment of bio-based materials´ end-of-life. Therefore, they suggest a full LCA of new generation bio-based materials for future research. Seolin dos Santos and de Souza Campos [132] identify, collect and organize post-consumer textile waste practices: collection, sorting, reuse, and recycling. While Stenton et al. [139] focus on collaborative fashion consumption.

In 2022, there are only three reviews so far, but others still can be published since the present research stopper the search for new materials in August 2022. Alves et al. [3] stand out with a review of current approaches and technologies for traceability in the textile and clothing value chain. These approaches and technologies include blockchain and the internet of things, which are major hotspots in current fashion business models [66] (Fig. 8).

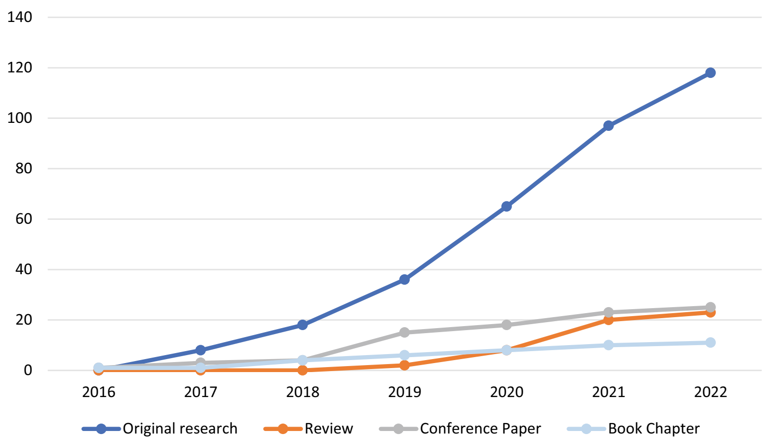


Fig. 8 Type of publications for keyword combination group 2, by year, accumulated

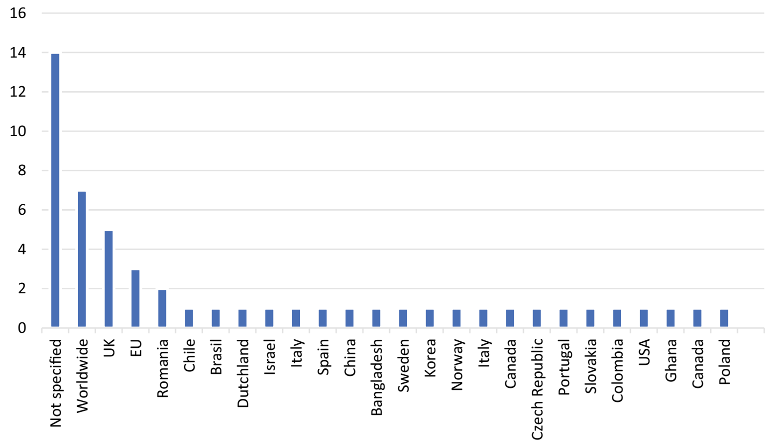


Fig. 9 Geographical scope of publications from group two keyword combination

3.2.2 CE and Clothing, Geographical Scope

From the reviewed publications, 14 did not specify a geographical scope, and seven have a worldwide scope. The other publications study one or several specific countries. Being the UK, the most studied country, in five publications. Three publications study Europe as a whole, and two study Romania. The rest of the countries are studied once (Fig. 9).

3.2.3 Top Scientific Journals

Journal articles, including original research and reviews, are published in 74 different journals. The top four publishers are *Sustainability (MDPI)*, *Journal of Cleaner Production (Elsevier)*, *Business Strategy and the Environment (Wiley)*, and *Journal of Fashion Marketing and Management (Emerald)*. 25 of 74 journals are journals with a corporate and business focus (Table 8).

Table 8 Top four CE and clothing publishers

Publication source	Number
Sustainability	22
Journal of Cleaner Production	17
Business Strategy and the Environment	5
Journal of Fashion Marketing and Management	5

3.3 Group Three. Research Combining "Circular Economy and LCA", and "Clothing", "Fashion", and "Apparel" Keywords

The application of the third group of keyword combinations "circular economy and LCA", and "clothing", "fashion", and "apparel", resulted in 565 publications. After applying the filtration criteria explained in the methods section and shown in Table 2, the number of publications was reduced to 1. This publication is a proceeding paper, published in the Design Journal *(Taylor and Francis)*, in 2019, describing a case study related to collaborative circular thinking [53], which will be discussed in the next sections (Table 9).

3.4 Connections Between LCA and CE in the Clothing Sector

This review shows that there is an increasing interest in addressing sustainability issues in the clothing industry. The body of literature available reviewing the implications of rethinking, recycling, reusing, and repurposing clothes keep growing over time [53, 57, 142, 149]. Some authors have framed their discussions using the CE concept, which has gained fast popularity in sustainability agendas, in the last years [81, 86]. Aiming to understand the connections between CE and LCA, and how LCA is currently informing CE strategies, we started by analyzing LCA literature.

We reviewed a total of 73 LCA papers, and we discovered that even when results could be useful in informing CE strategies, only twelve of them mention CE, which represents less than 17%. Nine of these twelve papers are original research papers and three are literature reviews. Based on the years of publication the connection between LCA and CE is quite recent. This fact is not a surprise, as CE is also an emerging concept. Six are published in 2021, one in 2019, three in 2018, one in 2017, and one in 2015. On the other hand, we reviewed 175 CE publications and discovered that only 21, 12% of the total, mention LCA. The proceeding paper resulting from the search using "CE" and "LCA" keywords together, mention both concepts from a circular design perspective [53], but works present a case study and the theoretical component of the document is not much developed.

We identified two big groups of publications. The first group includes papers developed from an LCA practitioner perspective, and the second group includes papers developed from a CE expert/researcher perspective. Within each group, there are authors that connect CE and LCA briefly, and others that develop the relationship between both frameworks much further (Table 10).

Table 9 Initial research and filtration processes for keyword combination group two

Keyword X	Keyword Y	Database	Papers identified	Title and keyword screening	Abstract screening	Duplicates elimination	Full text screening	Mendelay storage
			Records identified through database searching	Records after tittle and keyword screening (n-) for excluding obvious errors	Records after abstract screening (n-)	Number of papers with full text available after duplicates removed	Records after full text check	Number of papers with full text available stored in Mendelay
"Circular economy*" AND "LCA"	AND "clothing"	Scopus	0	0	0	0	0	0
"Circular economy*" AND "LCA"	AND "clothing"	WOS	6	5	5	4	0	0
"Circular economy*" AND "LCA"	AND "apparel"	Scopus	2	2	2	0	0	0
"Circular economy*" AND "LCA"	AND "apparel"	WOS	4	4	4	0	0	0
"Circular economy*" AND "LCA"	AND "fashion"	Scopus	0	0	0	0	0	0
"Circular economy*" AND "LCA"	AND "fashion"	WOS	2	2	2	1	1	1
		Total	14	13	13	5	1	1

Table 10 Connections between reviewed publications, CE, and LCA frameworks

Type of publication	Mentioning CE	Mentioning LCA
LCA original research	9	/
LCA literature reviews	3	/
CE original research	/	18
CE literature reviews	/	4

3.4.1 From the LCA Practitioner's Perspective

Most of the papers connecting LCA and CE, seven out of twelve, mention CE shortly and discuss the concept briefly. For instance, [75] calculate the pre-consumer waste footprint of 10 products, including trousers and training clothes. These authors mention briefly that advancing in the application of LCA to visualize and measure waste may contribute to the European Union Circular Economy Action Plan [45], which is focused on waste reduction. However, this claim was not further developed. Similarly, Moazzem et al. [88] quickly comment that by adopting efficient pattern-making skills and technology, as well as introducing innovative designs, the clothing industry could reduce production waste, which is very significant for circular economies. Moazzem et al. [89] mentions that LCA is widely used in many areas, including the evaluation of CE.

There are five LCA papers that discuss or work with the CE concept further. In these papers we have identified a consistent use of LCA to inform CE claims and strategies empirically. Wiedemann et al. [155] analyze how garment care best practices can reduce the environmental impact of clothing. Johnson and Plepys [67] study the sustainability of product-service systems (PSS), which are often seen as pathways to more sustainable societies. Castellani et al. [16] asses the impacts of clothing reusing. Martin and Herlaar [86] evaluate the environmental performance of valorizing waste wool for sweater production. Payet [108] presents a project in which French textile manufacturers quantify the carbon footprint of sold clothes using LCA.

Johnson and Plepys [67] and Martin and Herlaar [86] justify their studies, claiming that alternatives to conventional business models are needed to address current environmental issues [104, 114]. Johnson and Plepys [67] present a very detailed theoretical framework of how PSS fit into the group of business models based on ideologies under the circular economy.

Johnson and Plepys [67] discuss that despite the sustainability potential of circular business models, some may not result in reduced consumption and that the sustainability outcomes of PSS are not certain or clear [5, 12]. Similarly, Martin and Herlaar [86] point out that while many studies present theoretical examples of possible circular solutions in fashion, creating expectations for their potential, few studies provide empirical evidence. In fact, there is a recognized gap between logical claims and empirical evidence of the practical application of CE strategies [4, 86, 98].

For instance, the environmental benefits of reuse service strategies depend on their ability to displace primary production and minimize the associated impacts [167]. Despite PSS, such as clothing libraries, can reduce the speed of fashion if garments are used more times, they also have the potential to promote consumption if customers increase the frequency in which they update their closets [163]. Being part of clothing-sharing initiatives may not prevent waste since users who rent some clothes may not abstain from purchasing others [26].

In this context, Johnson and Plepys [67] apply LCA to compare rental business models and linear ownership models. The results confirm that the potential benefits of rental clothing depend on how many times consumers wear garments, how the rental activity substitutes their purchasing needs, and how they travel to rental stores. Martin and Herlaar [86] apply LCA to compare valorized and conventional wool sweater production and confirm that the supply chain valorizing waste wool significantly reduces environmental impacts compared to conventional supply chains of merino wool. Additionally, their results show that wool processing and sweater assembly have the largest share of environmental impacts but are sensitive to the energy mix employed.

Wiedemann et al. [155] compare six best and worst-case circular practice scenarios, related to maintenance, recovery, redistribution, and remanufacturing activities. The results show that washing clothes less frequently, using more efficient washing machines, reducing the use of dryers, and extending the number of times clothes are used by different users, have the potential to reduce clothing footprint. Moazzem et al. [91] also argue that textile reuse and recycling process involves a circularity approach, where fabric can be used at its highest value.

Payet [108] discusses that the challenge of a circular economy is to form a closed loop of used materials, and states that significant efforts implemented in the last 10 years have stimulated the reuse and recycling of clothing products in France and have reduced the sector´s emissions considerably. Additionally, based on LCA results, and to reduce the carbon footprint of French clothing further, the author recommends locating textile production in countries with low carbon electricity, reducing unsold items, and to incorporating eco-design strategies.

3.4.2 From the CE Researcher's Perspective

CE aims to promote economic, social, and environmental performance and resilience. It has been thought as a system in which resource inputs and output leakage is minimized, by closing and narrowing material and energy loops [116]. Our research shows that the CE paradigm has become a vibrant area of research and a hot topic in debates about new and sustainable economic production models, and strategic management [14, 25, 28, 42, 85, 118, 138, 144].

CE is associated with four main "loops": (1) product-life extension: designing for durability and extended lifetime; (2) reuse; (3) remanufacturing and refurbishing; and (4) recycling [40, 51, 59, 148] Some of the authors addressing this loops include: (1) for product-life extension: Olaru and Badea [102], Avadanei et al. (2021), and Cooper

Table 11 Top 3 approaches in CE papers and publications sample

Approach	Sample of publications
Consumer perceptions and attitudes toward circular economy in general	[6, 15, 24, 54, 62, 69, 71, 97, 127, 142, 166]
Business strategy and models	[14, 25, 28, 42, 85, 118, 138, 144]
Recycle and upcycle	[65, 92, 101, 121, 136]

and Claxton (2022); (2) for reuse: Albu et al. [2], Shirvanimoghaddam et al. [136], and Williams and Powell [156], (3) for remanufacturing: Diddi and Yan [34], Laitala et al. [72], and Shirvanimoghaddam et al. [136], (4) for recycle and upcycle: James and Kent [65], Morais et al. [92], Norris [101], Riba et al. [121], and Shirvanimoghaddam et al. [136].

From the total amount of reviewed CE papers, consumer perceptions and attitudes toward CE, business strategy and business models, and recycle and upcycle were the top three approaches studies (see Table 11). It has been identified that different from LCA publications, in CE publications the economic and market approach prevails.

Mentions of LCA in CE publications are superficial, and the LCA method is not explicitly applied to inform the CE framework, except for one paper [141]. In most papers, general and short statements in regard to LCA were found. For instance, Urbinati et al. [148] introduce LCA as one of the methods that has been used to assess potential environmental benefits of various CE systems. Provin et al. [116] name LCA as an option while discussing the need to conduct in-depth studies in the pursue of sustainable societies. Piippo et al. [113] say that corporate responsibility can be tracked trough certifications and LCA studies. Neto et al. [98] review the literature on bio recycling and circular economy opportunities and discover that only two out of twenty-two publications applied a quantitative assessment. One applied LCA.

Wagner and Heinzel [151] conduct a systematic review on human perceptions of recycled textile and circular fashion and identifies that a significant portion of consumers have a basic understanding about product sustainability. Some industry sections are more aware and recognize the need for sustainability, others such as designers need to improve. Awareness is influenced by various factors, and the limited real contribution of CE strategies is one of them. In this context, the authors highlight the need for more LCA studies.

Subramanian et al. [141] develop a very complete overview of cotton and polyester, and their valorization to value-added products, from a CE approach. The authors review recent efforts to recycle solid waste from textile industries, and present detailed information on the types of solid waste generated, pretreatment encompassing the regeneration of fibers, value-added products, and their applications. Also, the authors discuss challenges in managing waste streams through valorizations techniques and potential solutions. The overview specifically aims at informing researchers and practitioners toward the design of efficient strategies for waste streams management. This paper was the only publication that includes an LCA and a technoeconomic assessment (TEA) to present informed recommendations.

3.4.3 From the Designer's Perspective

Circular design and sustainable design overlap in ethos and approach, but the first one is more focused on the economic dimension [36, 109]. The design phase can contribute substantially to the environmental impact of products; nevertheless, the academic design research still lacks exploration on the contribution of design to circular business models [109]. Several approaches and tools are now available to assist designers to make an informed decision [36]. During this review, we have identified two papers from the design perspective, that briefly recognize LCA as a suitable tool to provide criteria and evidence during the design face [23, 53].

Goldsworthy and Ellams [53] reflect on the emerging field of design for the circular economy, and the need to connect traditionally unconnected fields, like LCA, to achieve circularity goals. They claim that existing life cycle tools are mainly applied for the auditing products at post-production stages—science based, or at ideation stages—lacking scientific basis. They present an interesting case study that integrates material scientists, industry stakeholders, consumer behavior, and LCA researchers into the heart of an iterative design process, as an experiment of a closer interdisciplinary collaboration. Claxton and Kent [23] also confirm that LCA is suitable to map the entire fashion supply chain and provide designers with criteria and evidence for selecting sustainable design strategies. However, these authors don´t develop any further. Bases on these publications it could be said that the designer could have an important role in integrating CE and LCA frameworks.

4 Conclusions

While the clothing sector brings many benefits to societies, it is also one of the most environmentally harmful industries in the world. Traditional methods of production require an intensive use of resources like toxic chemicals, water, and energy; and generate a substantial amount of polluting waste. For this reason, the clothing industry is at the center of increasing attention from sustainability practitioners. LCA and CE practitioners are not the exception and the number of publications from LCA and CE perspectives keeps growing. We conducted a systematic literature review to evaluate LCA and CE literature and to understand how these frameworks have been applied in the clothing context.

We reviewed 253 publications, including journal articles, books, book chapters, and conference papers. The application of keywords resulted in two big groups of publications: LCA publications and CE publications. We also tried to obtain a third group of publications by combining LCA and CE keywords in the same research, but we only got one paper about fashion circular design. Not surprisingly, LCA publications on clothing started appearing since 1997, while CE publications started appearing almost 20 years later. This difference in time reflects the history of each framework. LCA has been in development since the 90 s, and CE has started to gain momentum in the last 10 years. We reviewed a total of 46 original LCA research papers which results can perfectly inform CE strategies. Five of these papers were specifically focused on informing CE strategies.

On the other hand, CE publications were more recent, but the rate at which the number of CE publications grows is higher than the LCA publications. In this sense, this research area could be considered emerging. The reviewed CE publications are mostly focused on consumer and other stakeholder perceptions, and evidence a market and business focus. The fact that CE claims are still lacking empirical evidence is highlighted by several authors. In this context stating that currently promoted generic circular fashion strategies have better environmental performance than traditional strategies in some cases could be theoretical and inexact. Therefore, a closer relationship with empirical and methodic frameworks such as LCA is required and further research to translate concepts into positive environmental outcomes, that are currently much needed.

References

1. Aguiar et al (2021) https://www.mdpi.com/2071-1050/13/21/12246
2. Albu AV, Caciora T, Berdenov Z, Ilies DC, Sturzu B, Sopota D, Herman GV, Ilies A, Kecse G, Ghergheles CG (2021) Digitalization of garment in the context of circular economy. Industria Textila 72(1):102–107. https://doi.org/10.35530/IT.072.01.1824
3. Alves L, Ferreira Cruz E, Lopes SI, Faria PM, Rosado da Cruz AM (2022) Towards circular economy in the textiles and clothing value chain through blockchain technology and IoT: a review. In: Waste management and research, vol 40, issue 1. SAGE Publications Ltd, pp 3–23. https://doi.org/10.1177/0734242X211052858
4. Amasawa E, Shibata T, Sugiyama H, Cleaner MHJ et al. (2020) Environmental potential of reusing, renting, and sharing consumer products: systematic analysis approach. Elsevier. https://www.sciencedirect.com/science/article/pii/S0959652619333578?casa_token=YNA7WUEVtUgAAAAA:DKiRgpmqtmIqi7Z88En8_iL-jfSRNMKwkT8wi4XeYKDjGN1K0iVPC0hF_aC4A5ilZHcR6Vc
5. Amaya J, Lelah A, Zwolinski P (2014) Design for intensified use in product–service systems using life-cycle analysis. J Eng Des 25:280–302. https://doi.org/10.1080/09544828.2014.974523
6. Baier D, Rausch TM, Wagner TF (2020) The drivers of sustainable apparel and sportswear consumption: a segmented kano perspective. Sustainability (Switzerland) 12(7). https://doi.org/10.3390/su12072788
7. Barnes EM, Daystar JS, Wallace ML (2018) Challenges of conducting a life cycle assessment for bio-based materials using a cotton example. ASABE 2018 annual international meeting, vol 1. https://doi.org/10.13031/AIM.201800013
8. Baydar G, Ciliz N, Mammadov A (2015) Life cycle assessment of cotton textile products in Turkey. Resour Conserv Recycl 104:213–223. https://doi.org/10.1016/j.resconrec.2015.08.007
9. Bhardwaj V, Fairhurst A (2010) Fast fashion: response to changes in the fashion industry. Int Rev Retail Distrib Consum Res 20(1):165–173. https://doi.org/10.1080/09593960903498300

10. Bjørn A, Owsianiak M, Molin C, Hauschild MZ (2017) LCA history. Life Cycle Assessment: Theory Pract. https://doi.org/10.1007/978-3-319-56475-3_3
11. Blum P (2021) Circular fashion: making the fashion industry sustainable. https://books.google.com/books?hl=es&lr=&id=BT5PEAAAQBAJ&oi=fnd&pg=PT8&dq=Circular+fashion+peggy&ots=EZVvRLVTtP&sig=ne90DBPgfcxbnoZqYYa3Ugt9QKU
12. Böcker L, Meelen T (2017) Sharing for people, planet or profit? Analysing motivations for intended sharing economy participation. Environ Innov Soc Trans 23:28–39. https://doi.org/10.1016/J.EIST.2016.09.004
13. Bressanelli G, Visintin F, Saccani N (2021) Circular economy and the evolution of industrial districts: a supply chain perspective. https://doi.org/10.1016/j.ijpe.2021.108348
14. Brydges T (2021) Closing the loop on take, make, waste: Investigating circular economy practices in the Swedish fashion industry. J Clean Prod 293:126245. https://doi.org/10.1016/J.JCLEPRO.2021.126245
15. Camacho-Otero J (2019) Consumer engagement in the circular economy: exploring clothes swapping in emerging economies from a social practice perspective. Wiley Online Library 28(1):279–293. https://doi.org/10.1002/sd.2002
16. Castellani V, Sala S (2013) Beyond the throwaway society: a life cycle-based assessment of the environmental benefit of reuse. Wiley Online Library 11(3):373–382. https://doi.org/10.1002/ieam.1614
17. Castro-López A, Iglesias V, Puente J (2021) Slow fashion trends: are consumers willing to change their shopping behavior to become more sustainable? Sustainability 13(24):13858. https://doi.org/10.3390/SU132413858
18. Chapagain A, Hoekstra A, Savenije H, Gautam R (2005) The water footprint of cotton consumption. https://research.utwente.nl/en/publications/the-water-footprint-of-cotton-consumption
19. Chen X, Memon HA, Wang Y, Marriam I, Tebyetekerwa M (2021) Circular economy and sustainability of the clothing and textile industry. Mater Circ Econ 3(1). https://doi.org/10.1007/s42824-021-00026-2
20. Circular Economy | World Economic Forum (n.d.). Retrieved August 5, 2022, from https://www.weforum.org/projects/circular-economy
21. Circularity | UNEP - UN Environment Programme (n.d.). Retrieved August 5, 2022, from https://www.unep.org/circularity
22. Claudio L (2007) Waste couture: environmental impact of the clothing industry. Environ Health Perspect 115(9). https://doi.org/10.1289/EHP.115-A449
23. Claxton S, Kent A (2020) The management of sustainable fashion design strategies: an analysis of the designer's role. J Clean Prod 268:122112. https://doi.org/10.1016/J.JCLEPRO.2020.122112
24. Colasante A, D'Adamo I (2021) The circular economy and bioeconomy in the fashion sector: emergence of a "sustainability bias." J Clean Prod 329:129774. https://doi.org/10.1016/J.JCLEPRO.2021.129774
25. Colucci M, Vecchi A (2021) Close the loop: evidence on the implementation of the circular economy from the Italian fashion industry. Bus Strateg Environ 30(2):856–873. https://doi.org/10.1002/BSE.2658
26. Corvellec H, Stål HI (2017) Evidencing the waste effect of Product-Service Systems (PSSs). J Clean Prod 145:14–24. https://doi.org/10.1016/J.JCLEPRO.2017.01.033
27. Dahlbo H, Aalto K, Eskelinen H, Salmenperä H (2017) Increasing textile circulation—consequences and requirements. Sustain Prod Consum 9:44–57. https://doi.org/10.1016/J.SPC.2016.06.005
28. Daňo F, Drábik P, Review EH-CEB (2020) Circular business models in textiles and apparel sector in Slovakia. Cebr.vse.Cz. https://doi.org/10.18267/j.cebr.226
29. Das M, Herweyers L, Moons I, du Bois E (2021) Strategic design opportunities to increase sustainable fashion awareness and behaviour. Proc Des Soc 1:2711–2720. https://doi.org/10.1017/pds.2021.532

30. Daystar J, Chapman L, Moore M, Pires S, Golden J (2019) Quantifying apparel consumer use behavior in six countries: addressing a data need in life cycle assessment modeling. JTATM 11(1)
31. de Aguiar Hugo A, de Nadae J, Da R, Lima S, Shimomura Y, Hosono S (2021) Can fashion be circular? A literature review on circular economy barriers, drivers, and practices in the fashion industry's productive chain. Sustainability 13(21):12246. https://doi.org/10.3390/SU132112246
32. Defra UK (2011) Guidance on applying the waste hierarchy. https://scholar.google.com/scholar?hl=es&as_sdt=0%2C5&q=Guidance+on+applying+the+waste+hierarchy&btnG
33. Dey PK, Malesios C, De D, Budhwar P, Chowdhury S, Cheffi W (2020) Circular economy to enhance sustainability of small and medium-sized enterprises. Bus Strateg Environ 29(6):2145–2169. https://doi.org/10.1002/BSE.2492
34. Diddi S, Yan RN (2019) Consumer perceptions related to clothing repair and community mending events: a circular economy perspective. Sustainability (Switzerland) 11(19). https://doi.org/10.3390/su11195306
35. Druckman A, Jackson T (2010) An exploration into the carbon footprint of UK households. Sock Res 02–10. http://resolve.sustainablelifestyles.ac.uk/sites/default/files/RESOLVE_WP_02-10.pdf
36. Earley R, Goldsworthy K (2018) Circular textile design: old myths and new models. In: Designing for the circular economy. Routledge, pp 175–185
37. Ecotextiles (n.d.) Textile industry poses environmental hazards
38. Eder-Hansen J, Kryger J, Sisco C, Watson D, Kiorboe N, Burchardi I (2012) The nice consumer (Research Summary and Discussion Paper toward a framework for sustainable fashion in the EU). Danish Fashion Institute. https://scholar.google.com/scholar?hl=es&as_sdt=0%2C5&q=The+nice+consumer&btnG
39. Ellen Macarthur Foundation (2013) Toward the circular economy
40. Ellen MacArthur Foundation (2017) A new textiles economy: Redesigning fashion future
41. Eryuruk SH (2012) Greening of the textile and clothing industry. Fibres Text Eastern Eur 20(95):22–27. https://www.infona.pl/resource/bwmeta1.element.baztech-article-BPW7-0024-0009
42. Esbeih KN, Molina-Moreno V, Núñez-Cacho P, Silva-Santos B (2021) Transition to the circular economy in the fashion industry: the case of the inditex family business. Sustainability (Switzerland) 13(18). https://doi.org/10.3390/su131810202
43. Esteve-Turrillas FA, de la Guardia M (2017) Environmental impact of Recover cotton in textile industry. Resour Conserv Recycl 116:107–115. https://doi.org/10.1016/J.RESCONREC.2016.09.034
44. Ethical Consumer (n.d.) Fast fashion's addiction to synthetic fibres. Retrieved 19 March 2022, from https://www.ethicalconsumer.org/fashion-clothing/fast-fashions-addiction-synthetic-fibres
45. European Comission (2020) A new circular economy action plan. Retrieved March 19, 2022, from https://eur-lex.europa.eu/legalcontent/EN/TXT/HTML/?uri=CELEX:52020DC0098&from=EN
46. Farrant L, Olsen SI, Wangel A (2010) Environmental benefits from reusing clothes. Int J Life Cycle Assess 15(7):726–736. https://doi.org/10.1007/S11367-010-0197-Y
47. Fletcher K (2009) Systems change for sustainability in textiles. In: Sustainable textiles. Elsevier, pp 369–380
48. Fletcher K (2013) Sustainable fashion and textiles: design journeys, second edition. Sustainable fashion and textiles: design journeys, second edition, pp 1–267. https://doi.org/10.4324/9781315857930/SUSTAINABLE-FASHION-TEXTILES-KATE-FLETCHER
49. Fung Y-N, Choi T-M (2018) Product development process of an international luxury fashion brand: implications to Hong Kong fashion trading and manufacturing companies, pp 27–41. https://doi.org/10.1007/978-981-10-7007-5_2
50. Gazzola P, Pavione E, Pezzetti R (2020) Trends in the fashion industry. The perception of sustainability and circular economy: a gender/generation quantitative approach. Sustainability. https://doi.org/10.3390/su12072809

51. Geissdoerfer M, Savaget (2017) The circular economy–a new sustainability paradigm? J Cleaner Prod
52. Global Fashion Agenda (GFA), and The Boston Consulting Group (BCG) (2017) Pulse of the fashion industry—global fashion agenda. https://globalfashionagenda.org/impact-initiatives/pulse-of-the-industry/
53. Goldsworthy K, Ellams D (2019) Collaborative circular design. incorporating life cycle thinking into an interdisciplinary design process. https://doi.org/10.1080/14606925.2019.1595416
54. Gomes GM, Moreira N, Bouman T, Ometto AR, van der Werff E (2022) Towards circular economy for more sustainable apparel consumption: testing the value-belief-norm theory in Brazil and in The Netherlands. Sustainability (Switzerland) 14(2). https://doi.org/10.3390/su14020618
55. Gonçalves A, Silva C (2021) Looking for sustainability scoring in apparel: a review on environmental footprint, social impacts and transparency. In: Energies, vol 14, issue 11. MDPI AG. https://doi.org/10.3390/en14113032
56. Graedel TE (1997) Designing the ideal green product: LCA/SCLA in reverse. Int J Life Cycle Assess 2(1):25–31. https://doi.org/10.1007/BF02978714
57. Han SLC, Chan PYL, Venkatraman P, Apeagyei P, Cassidy T, Tyler DJ (2017) Standard vs. upcycled fashion design and production. Fashion Pract 9(1):69–94. https://doi.org/10.1080/17569370.2016.1227146
58. Härtsiä A (2018) Future of sustainability in fast fashion. https://www.theseus.fi/handle/10024/140544
59. Hazen B (2016) Remanufacturing for the circular economy: an examination of consumer switching behavior. Wiley Online Lib 26(4):451–464. https://doi.org/10.1002/bse.1929
60. Henry BK, Russell SJ, Ledgard SF, Gollnow S, Wiedemann SG, Nebel B, Maslen D, Swan P (2015) LCA of wool textiles and clothing. In: Handbook of life cycle assessment (LCA) of textiles and clothing. Elsevier Inc, pp 217–254. https://doi.org/10.1016/B978-0-08-100169-1.00010-1
61. Hole G, Hole A (2019) Recycling as the way to greener production: a mini review. J Clean Prod 212:910–915
62. Hur E (2020) Rebirth fashion: Secondhand clothing consumption values and perceived risks. J Clean Prod 273:122951. https://doi.org/10.1016/J.JCLEPRO.2020.122951
63. ISO (2016a) ISO 14040:2006 environmental management—life cycle assessment—principles and framework. Retrieved 19 March 2022, from https://www.iso.org/standard/37456.html
64. ISO (2016b) ISO 14044:2006 environmental management—life cycle assessment—requirements and guidelines. Retrieved 19 March 2022, from https://www.iso.org/standard/38498.html
65. James ASJ, Kent A (2019) Clothing sustainability and upcycling in ghana. Fash Pract 11(3):375–396. https://doi.org/10.1080/17569370.2019.1661601
66. Jin Y, Song X, Tang J, Dong X, Ji H (2021) Business model of garment enterprises: a scientometric review. Text Res 91(13–14):1609–1626. https://doi.org/10.1177/0040517520985908
67. Johnson E, Plepys A (2021) Product-service systems and sustainability: analysing the environmental impacts of rental clothing. Sustainability (Switzerland) 13(4):1–30. https://doi.org/10.3390/su13042118
68. Kazan H, Akgul D, Kerc A (2020) Life cycle assessment of cotton woven shirts and alternative manufacturing techniques. Clean Technol Environ Policy 22(4):849–864. https://doi.org/10.1007/S10098-020-01826-X
69. Kim I, Jung HJ, Lee Y (2021) Consumers' value and risk perceptions of circular fashion: comparison between secondhand, upcycled, and recycled clothing. Sustainability (Switzerland) 13(3):1–23. https://doi.org/10.3390/su13031208
70. Kirchherr J, Reike D, Resources MH (2017) Conceptualizing the circular economy: an analysis of 114 definitions. Elsevier. https://www.sciencedirect.com/science/article/pii/S0921344917302835

71. Koszewska M, Rahman O, Dyczewski B (2020) Circular fashion—consumers' attitudes in cross-national study: Poland and Canada. Autex Research Journal 20(3):327–337. https://doi.org/10.2478/AUT-2020-0029
72. Laitala K, Klepp IG, Haugrønning V, Throne-Holst H, Strandbakken P (2021) Increasing repair of household appliances, mobile phones and clothing: experiences from consumers and the repair industry. J Clean Prod 282:125349. https://doi.org/10.1016/J.JCLEPRO.2020.125349
73. Laitala K, Klepp IG, Henry B (2018) Does use matter? Comparison of environmental impacts of clothing based on fiber type. Sustain (Switzerland) 10(7). https://doi.org/10.3390/su10072524
74. Laitla K, Klepp IG, Henry B (2017) Use phase of wool apparel: a literature review for improving LCA. In: 2nd conference on product lifetimes and the environment (PLATE)
75. Laurenti R, Moberg Å, Stenmarck Å (2017) Calculating the pre-consumer waste footprint: a screening study of 10 selected products. Waste Manage Res 35(1):65–78. https://doi.org/10.1177/0734242X16675686
76. Lecerf L, De L, Skinner A, De S, Kunz S, De K (2017) Moving towards a circular economy with EMAS. Publications Office of the European Union
77. Li X, Chen L, Ding X (2019) Allocation methodology of process-level carbon footprint calculation in textile and apparel products. Sustainability (Switzerland) 11(16). https://doi.org/10.3390/su11164471
78. Life Cycle Assessment—IPP—Environment—European Commission. (n.d.). Retrieved 3 Aug 2022, from https://ec.europa.eu/environment/ipp/lca.htm
79. Liu Y, Zhu L, Zhang C, Ren F, Huang H, Liu Z (2020) Life cycle assessment of melange yarns from the manufacturer perspective. Int J Life Cycle Assess 25(3):588–599. https://doi.org/10.1007/S11367-019-01705-8
80. Livia Firth (2015) The true cost. https://truecostmovie.com/
81. López NM, Sáenz JLS, Biedermann A, Tierz AS (2020) Sustainability assessment of product-service systems using flows between systems approach. Sustainability (Switzerland) 12(8). https://doi.org/10.3390/SU12083415
82. Luo Y, Song K, Ding X, Wu X (2021) Environmental sustainability of textiles and apparel: a review of evaluation methods. Environ Impact Assess Rev 86:106497. https://doi.org/10.1016/J.EIAR.2020.106497
83. Machado MAD, de Almeida SO, Bollick LC, Bragagnolo G (2019) Second-hand fashion market: consumer role in circular economy. J Fash Mark Manag 23(3):382–395. https://doi.org/10.1108/JFMM-07-2018-0099
84. Manda BMK, Worrell E, Patel MK (2015) Prospective life cycle assessment of an antibacterial T-shirt and supporting business decisions to create value. Resour Conserv Recycl 103:47–57. https://doi.org/10.1016/j.resconrec.2015.07.010
85. Marques AD, Marques A, Ferreira F (2020) Homo Sustentabilis: circular economy and new business models in fashion industry. SN Appl Sci 2(2). https://doi.org/10.1007/s42452-020-2094-8
86. Martin M, Herlaar S (2021) Environmental and social performance of valorizing waste wool for sweater production. Sustain Prod Consum 25:425–438. https://doi.org/10.1016/J.SPC.2020.11.023
87. Meyer DE, Curran MA, Gonzalez MA (2011) An examination of silver nanoparticles in socks using screening-level life cycle assessment. J Nanopart Res 13(1):147–156. https://doi.org/10.1007/s11051-010-0013-4
88. Moazzem S, Crossin E, Daver F, Wang L (2021) Life cycle assessment of apparel consumption in Australia. Environ Clim Technol 25(1):71–111. https://doi.org/10.2478/RTUECT-2021-0006
89. Moazzem S, Crossin E, Daver F, Wang L (2021) Assessing environmental impact reduction opportunities through life cycle assessment of apparel products. Sustain Prod Consum 28:663–674. https://doi.org/10.1016/J.SPC.2021.06.015

90. Moazzem S, Daver F, Crossin E, Wang L (2018) Assessing environmental impact of textile supply chain using life cycle assessment methodology. J Text Inst 109(12):1574–1585. https://doi.org/10.1080/00405000.2018.1434113
91. Moazzem S, Wang L, Daver F, Crossin E (2021) Environmental impact of discarded apparel landfilling and recycling. Resour Conserv Recycl 166:105338. https://doi.org/10.1016/J.RESCONREC.2020.105338
92. Morais C, Carvalho C, Montagna G (2020) Dynamic wardrobe from a user's perspective—a previous survey study for female students. Adv Intell Syst Comput 954:358–364. https://doi.org/10.1007/978-3-030-20444-0_35
93. Munasinghe P, Druckman A, Dissanayake DGK (2021) A systematic review of the life cycle inventory of clothing. J Clean Prod. https://doi.org/10.1016/J.JCLEPRO.2021.128852
94. Muthu SS (2015) Introduction. In: Handbook of life cycle assessment (LCA) of textiles and clothing. Woodhead publishing
95. Muthukumarana TT, Karunathilake HP, Punchihewa HKG, Manthilake MMID, Hewage KN (2018) Life cycle environmental impacts of the apparel industry in Sri Lanka: analysis of the energy sources. J Clean Prod 172:1346–1357. https://doi.org/10.1016/J.JCLEPRO.2017.10.261
96. Nagaraj AR (2015) Energy management in textile industry
97. Nencková L, Pecáková I, Šauer P (2020) Disposal behaviour of Czech consumers towards textile products. Waste Manage 106:71–76. https://doi.org/10.1016/J.WASMAN.2020.03.001
98. Neto GC, de O, Teixeira MM, Souza GLV, Arns VD, Tucci HNP, Amorim M (2022) Assessment of the eco-efficiency of the circular economy in the recovery of cellulose from the shredding of textile waste. Polymers 14(7). https://doi.org/10.3390/polym14071317
99. Nieminen-Kalliala E (n.d.) Environmental indicators of textile products for ISO (TYPE III) environmental product declaration. AUTEX Res J 3
100. Niinimäki K, Peters G, Dahlbo H, Perry P, Rissanen T, Gwilt A (2020) The environmental price of fast fashion. In: Nature reviews earth and environment, vol 1, issue 4. Springer Nature, pp 189–200. https://doi.org/10.1038/s43017-020-0039-9
101. Norris L (2019) Waste, dirt and desire: fashioning narratives of material regeneration. Sociol Rev 67(4):886–907. https://doi.org/10.1177/0038026119854273
102. Olaru S, Badea I (2020) Circular product design assessment applied to clothing products. In: ICAMS proceedings of the international conference on advanced materials and systems, pp 429–434. https://doi.org/10.24264/icams-2020.IV.15
103. O'Rourke D (2014) The science of sustainable supply chains. Science 344(6188):1124–1127. https://doi.org/10.1126/SCIENCE.1248526
104. Pal R (2016) Extended responsibility through servitization in PSS: an exploratory study of used-clothing sector. J Fash Mark Manag 20(4):453–470. https://doi.org/10.1108/JFMM-12-2015-0100/FULL/PDF
105. Pandey K (2018) Fashion industry may use quarter of world's carbon budget by 2050. https://www.downtoearth.org.in/news/environment/fashion-industry-may-use-quarter-of-world-s-carbon-budget-by-2050-61183
106. Parisi ML, Fatarella E, Spinelli D, Pogni R, Basosi R (2015) Environmental impact assessment of an eco-efficient production for coloured textiles. J Cleaner Prod 108(PartA):514–524. https://doi.org/10.1016/j.jclepro.2015.06.032
107. Park J, Waqar Z (2022) Life cycle assessment of returnable mailers used for apparel electronic commerce: a case study in Canada. Packag Technol Sci. https://doi.org/10.1002/PTS.2653
108. Payet J (2021) Assessment of carbon footprint for the textile sector in France. Sustainability (Switzerland) 13(5):1–23. https://doi.org/10.3390/su13052422
109. Pedersen ERG, Earley R, Andersen KR (2019) From singular to plural: exploring organisational complexities and circular business model design. J Fashion Market Manage
110. Peña C, Civit B, Gallego-Schmid A, Druckman A, Caldeira-Pires A, Weidema B, Mieras E, Wang F, Fava J, Milà I, Canals L, Cordella M, Arbuckle P, Valdivia S, Fallaha S, Motta W (2020) Using life cycle assessment to achieve a circular economy, vol 10

111. Peters G, Sandin G (2019) Environmental prospects for mixed textile recycling in Sweden. ACS Publ 7(13):11682–11690. https://doi.org/10.1021/acssuschemeng.9b01742
112. Petrescu L, Fermeglia M (2016) Life cycle analysis applied to acrylic acid production process with different fuels for steam generation. Elsevier
113. Piippo R, Niinimäki K, Aakko M (2022) Fit for the future: garment quality and product lifetimes in a CE context. Sustainability (Switzerland) 14(2). https://doi.org/10.3390/su14020726
114. Pohl J, Suski P, Haucke F, Piontek FM, Jäger M (2019) Beyond production—the relevance of user decision and behaviour in LCA. Sustain Prod Life Cycle Eng Manage. https://doi.org/10.1007/978-3-030-12266-9_1/COVER
115. Prieto-Sandoval V, Jaca C, Ormazabal M (2018) Towards a consensus on the circular economy. J Clean Prod 179:605–615. https://doi.org/10.1016/J.JCLEPRO.2017.12.224
116. Provin AP, Dutra AR, de A, de Sousa e Silva Gouveia ICA, Cuba, ALV (2021) Circular economy for fashion industry: use of waste from the food industry for the production of biotextiles. Technol Forecast Soc Change 169:120858. https://doi.org/10.1016/J.TECHFORE.2021.120858
117. Qian W, Zhu J, Chen F, Ji X, Wang L, Wang X (2021) water footprint assessment of viscose staple fiber garments. Water Supply 21(5):2217–2232. https://doi.org/10.2166/WS.2021.040
118. Radhakrishnan S (2021) Circular economy in textiles and fashion. Environ Footprints Eco-Design of Prod Process. https://doi.org/10.1007/978-981-16-3698-1_6
119. Reike D, Vermeulen WJV, Witjes S (2018) The circular economy: new or Refurbished as CE 3.0?—exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. Resour Conserv Recycl 135:246–264. https://doi.org/10.1016/J.RESCONREC.2017.08.027
120. Remy N, Speelman E, Swartz S (2016) Style that's sustainable: a new fast-fashion formula. http://dln.jaipuria.ac.in:8080/jspui/bitstream/123456789/3091/1/Style-thats-sustainable-A-new-fast-fashion-formula.pdf
121. Riba JR, Cantero R, Canals T, Puig R (2020) Circular economy of post-consumer textile waste: classification through infrared spectroscopy. J Clean Prod 272:123011. https://doi.org/10.1016/J.JCLEPRO.2020.123011
122. Roos S, Zamani B, Sandin G, Peters GM, Svanström M (2016) A life cycle assessment (LCA)-based approach to guiding an industry sector towards sustainability: the case of the Swedish apparel sector. J Clean Prod 133:691–700. https://doi.org/10.1016/J.JCLEPRO.2016.05.146
123. Roy Choudhury AK (2014) Environmental impacts of the textile industry and its assessment through life cycle assessment, pp 1–39. https://doi.org/10.1007/978-981-287-110-7_1
124. Saha K, Dey PK, Papagiannaki E (2021) Implementing circular economy in the textile and clothing industry. Bus Strateg Environ 30(4):1497–1530. https://doi.org/10.1002/BSE.2670
125. Sandin G, Peters GM (2018) Environmental impact of textile reuse and recycling: a review. J Clean Prod 184:353–365. https://doi.org/10.1016/J.JCLEPRO.2018.02.266
126. Sandin G, Peters GM, Svanström M (2015) Using the planetary boundaries framework for setting impact-reduction targets in LCA contexts. Int J Life Cycle Assess 20(12):1684–1700. https://doi.org/10.1007/s11367-015-0984-6
127. Sandvik IM, Stubbs W (2019) Circular fashion supply chain through textile-to-textile recycling. J Fash Mark Manag 23(3):366–381. https://doi.org/10.1108/JFMM-04-2018-0058/FULL/HTML
128. Santiago DE, Hernández Rodríguez MJ, Pulido-Melián E (2021) Laundry wastewater treatment: review and life cycle assessment. J Environ Eng 147(10):03121001. https://doi.org/10.1061/(asce)ee.1943-7870.0001902
129. Saxce M, de Pesnel S (n.d.) LCA of bed sheets–some relevant parameters for lifetime assessment. Elsevier. Retrieved 28 July 2022, from https://www.sciencedirect.com/science/article/pii/S0959652612003502?casa_token=OTJdY7IqDkoAAAAA:YX0gDlZa6hg1EmN6UZn-BXU6EwmDrPWCp5jdps-oiE58vkeazRWH7E0f4vXhj7Lhioswx9c
130. Semba T, Sakai Y, Ishikawa M, Inaba A (2020) Greenhouse gas emission reductions by reusing and recycling used clothing in Japan. Sustainability (Switzerland) 12(19). https://doi.org/10.3390/su12198214

131. Senthilkannan Muthu S (ed) (2018). Sustainable innovations in apparel production. https://doi.org/10.1007/978-981-10-8591-8.pdf
132. Seolin dos SantosP, de Souza Campos L (2021) Practices for garment industry's post-consumer textile waste management in the circular economy context: an analysis on literature. Brazil J Oper Prod Manage 18(1):1–17. https://doi.org/10.14488/BJOPM.2021.004
133. Shen L, Patel MK (2008) Life cycle assessment of polysaccharide materials: a review. J Polym Environ 16(2):154–167. https://doi.org/10.1007/s10924-008-0092-9
134. Shen L, Worrell E (2010) Environmental impact assessment of man-made cellulose fibres. Elsevier
135. Sherburne A (2009) Sustainability through the supply chain. Sustainable textiles life cycle and environmental impact. Woodhead Publishing Limited, CRC Press, UK, pp 1–32
136. Shirvanimoghaddam K, Motamed B, Ramakrishna S, Naebe M (2020) Death by waste: fashion and textile circular economy case. Sci Total Environ 718:137317. https://doi.org/10.1016/J.SCITOTENV.2020.137317
137. Sohn J, Nielsen KS, Birkved M, Joanes T, Gwozdz W (2021) The environmental impacts of clothing: evidence from United States and three European countries. Sustain Prod Consum 27:2153–2164. https://doi.org/10.1016/j.spc.2021.05.013
138. Staicu D (2021) Characteristics of textile and clothing sector social entrepreneurs in the transition to the circular economy. Industria Textila 72(1):81–88. https://doi.org/10.35530/IT.072.01.202031
139. Stenton M, Houghton JA, Kapsali V, Blackburn RS (2021) Review the potential for regenerated protein fibres within a circular economy: lessons from the past can inform sustainable innovation in the textiles industry. Sustainability (Switzerland) 13(4):1–18. https://doi.org/10.3390/su13042328
140. Stenton M, Kapsali V, Blackburn RS, Houghton JA (2021) From clothing rations to fast fashion: utilising regenerated protein fibres to alleviate pressures on mass production. Energies 14(18):5654. https://doi.org/10.3390/EN14185654
141. Subramanian K, Sarkar MK, Wang H, Qin ZH, Chopra SS, Jin M, Kumar V, Chen C, Tsang CW, Lin CSK (2021) An overview of cotton and polyester, and their blended waste textile valorisation to value-added products: a circular economy approach–research trends, opportunities and challenges. Crit Rev Environ Sci Technol. https://doi.org/10.1080/10643389.2021.1966254
142. Ta AH, Aarikka-Stenroos L, Litovuo L (2022) Customer experience in circular economy: experiential dimensions among consumers of reused and recycled clothes. Sustainability (Switzerland) 14(1). https://doi.org/10.3390/su14010509
143. Terinte N, Manda BMK, Taylor J, Schuster KC, Patel MK (2014) Environmental assessment of coloured fabrics and opportunities for value creation: spin-dyeing versus conventional dyeing of modal fabrics. J Clean Prod 72:127–138. https://doi.org/10.1016/j.jclepro.2014.02.002
144. Thatta S, Polisetty A (2020) The future is circular: a case study on MUD jeans. FIIB Bus Rev. https://doi.org/10.1177/2319714520950163
145. The Circular Economy in Cities and Regions - OECD (n.d) Retrieved 5 Aug 2022, from https://www.oecd.org/regional/cities/circular-economy-cities.htm
146. Tseng S, Hung W (2014) A strategic decision-making model considering the social costs of carbon dioxide emissions for sustainable supply chain management. J Environ Manage
147. United Nations (2018) UN helps fashion industry shift to low carbon | UNFCCC. https://unfccc.int/news/un-helps-fashion-industry-shift-to-low-carbon
148. Urbinati A, Chiaroni D (2017) Towards a new taxonomy of circular economy business models. Elsevier
149. Vadicherla T, Saravanan D, Muthu SSK (2015) Polyester recycling—technologies, characterisation, and applications. In: Environmental footprints and eco-design of products and processes. Springer, Singapore, pp 149–165. https://doi.org/10.1007/978-981-287-643-0_7
150. Vehmas K, Raudaskoski A, Heikkilä P, Harlin A, Mensonen A (2018) Consumer attitudes and communication in circular fashion. J Fash Mark Manag 22(3):286–300. https://doi.org/10.1108/JFMM-08-2017-0079

151. Wagner MM, Heinzel T (2020) Human perceptions of recycled textiles and circular fashion: a systematic literature review. Sustainability (Switzerland) 12(24):1–27. https://doi.org/10.3390/SU122410599
152. Walser T, Demou E, Lang DJ, Hellweg S (2011) Prospective environmental life cycle assessment of nanosilver T-shirts. Environ Sci Technol 45(10):4570–4578. https://doi.org/10.1021/es2001248
153. Watson KJ, Wiedemann SG (2019) Review of methodological choices in LCA-based textile and apparel rating tools: key issues and recommendations relating to assessment of fabrics made from natural fibre types. Sustainability (Switzerland) 11(14). MDPI. https://doi.org/10.3390/su11143846
154. Wiedemann SG, Biggs L, Nebel B, Bauch K, Laitala K, Klepp IG, Swan PG, Watson K (2020) Environmental impacts associated with the production, use, and end-of-life of a woollen garment. Int J Life Cycle Assess 25(8):1486–1499. https://doi.org/10.1007/s11367-020-01766-0
155. Wiedemann SG, Biggs L, Nguyen QV, Clarke SJ, Laitala K, Klepp IG (2021) Reducing environmental impacts from garments through best practice garment use and care, using the example of a Merino wool sweater. Int J Life Cycle Assess 26(6):1188–1197. https://doi.org/10.1007/s11367-021-01909-x
156. Williams I, Powell L (2019). Sustainable resource management by students at higher education institutions. Detritus 6:11–24. https://doi.org/10.31025/2611-4135/2019.13813
157. Woolridge AC, Ward GD, Phillips PS, Collins M, Gandy S (2006) Life cycle assessment for reuse/recycling of donated waste textiles compared to use of virgin material: an UK energy saving perspective. Resour Conserv Recycl 46(1):94–103. https://doi.org/10.1016/j.resconrec.2005.06.006
158. Yacout D, Assessment, M. H.-E. Monitoring and, and 2016, undefined (2016) Identifying potential environmental impacts of waste handling strategies in textile industry. Springer 188(8). https://doi.org/10.1007/s10661-016-5443-8
159. Yamaguchi Y, Seii E, Itagaki M, Nagayama M (2011) Evaluation of domestic washing in Japan using life cycle assessment (LCA). Int J Consum Stud 35(2):243–253. https://doi.org/10.1111/j.1470-6431.2010.00975.x
160. Yang Y, He W, Chen F, Wang L (2020) Water footprint assessment of silk apparel in China. J Clean Prod 260:121050. https://doi.org/10.1016/J.JCLEPRO.2020.121050
161. Yoo F, Jung HJ, Oh K (2021) Motivators and barriers for buying intention of upcycled fashion products in China. Sustainability 13(5):2584. https://doi.org/10.3390/SU13052584
162. Yun C, Islam M, LeHew M, Polymers (2016) Assessment of environmental and economic impacts made by the reduced laundering of self-cleaning fabrics. Springer 17(8):1296–1304. https://doi.org/10.1007/s12221-016-6320-3
163. Zamani B, Sandin G, Peters GM (2017) Life cycle assessment of clothing libraries: can collaborative consumption reduce the environmental impact of fast fashion? J Clean Prod 162:1368–1375. https://doi.org/10.1016/j.jclepro.2017.06.128
164. Zamani B, Svanström M, Peters G, Rydberg T (2015) A carbon footprint of textile recycling: a case study in Sweden. J Ind Ecol 19(4):676–687. https://doi.org/10.1111/JIEC.12208
165. Zanjirani Farahani R, Asgari N, van Wassenhove LN (2022) Fast fashion, charities, and the circular economy: challenges for operations management. Prod Oper Manag 31(3):1089–1114. https://doi.org/10.1111/poms.13596
166. Zhang X, Dong F (2021) How virtual social capital affects behavioral intention of sustainable clothing consumption pattern in developing economies? A case study of China. Resour Conserv Recycl 170:105616. https://doi.org/10.1016/J.RESCONREC.2021.105616
167. Zink T, Geyer R (2017) Circular economy rebound. J Indus Ecol 21(3):593–602. https://doi.org/10.1111/JIEC.12545

Life Cycle Assessment of the Renting of Leisurewear

Felix M. Piontek and Martin Müller

Abstract An increasing oversupply of clothing is linked to harmful environmental impacts. Women workers in the textile industry are exposed to poor working conditions. Renting clothing for a period of time instead of buying, using and disposing the garments is an emerging business model that might be suited to fulfill customers' needs for varied clothing while reducing the number of garments purchased and therefore the environmental impacts of the industry. This chapter presents a methodology to assess the environmental impacts of the use-based product-service systems (PSS) with the help of Life Cycle Assessment (LCA) using the example of clothing rental in Germany. Based on different scenarios, fashionistas are identified as a target group who can reduce their personal environmental impacts by adopting a rental model.

Keywords Life cycle assessment · Product-service system · LCA · PSS · Rental · Clothing · Consumer behavior

The current state of the clothing and textile as well as a rising demand for cheap clothes are linked to harmful impacts on the environment as well as poor working conditions of the people involved in the manufacturing of clothes [2, 11]. Business models of the Sharing Economy try to lower the environmental and social impacts of consumption by offering ways to have access to goods different from conventional consumption (in this chapter defined as the purchase, use and disposal of goods by one person). One emerging business model is the offer to rent garments for a certain period [1, 7]. While sharing goods might reduce the environmental impacts, this is not a given for every offer and every person. Therefore, the environmental impacts of newly emerging business models should be assessed to allow for a comparison with conventional ways of consumption as well as the optimization of the offering and derivation of guidelines for users.

F. M. Piontek · M. Müller (✉)
Institute of Sustainable Corporate Management, Ulm University, Helmholtzstr. 18, 89081 Ulm, Germany
e-mail: martin.mueller@uni-ulm.de

S. S. Muthu (ed.), *Progress on Life Cycle Assessment in Textiles and Clothing*,
Textile Science and Clothing Technology,
https://doi.org/10.1007/978-981-19-9634-4_5

The chapter presents the business model of renting clothes and outlines the challenges of assessing Product-Service Systems (PSS) with the help of Life Cycle Assessment (LCA). Subsequently, a methodological approach to assess the change of personal environmental impact if a rental offer is adapted by a single female user in Germany is presented. A result matrix of the 54 assessed scenarios and recommendations for users and companies offering clothing for rent closes the chapter.

1 Business Model: Renting of Leisurewear

Over the last two decades, start-ups that offer to rent garments online or offline instead of buying them appeared worldwide [6]. While offering additional services like styling advice, cleaning services, flat rate subscription and a broad range of styles from local designers to haute couture pieces is available, the basic process diagram looks similar for most of the services. An overview is depicted in Fig. 1. The diagram is based on research and interviews with start-up founders.

The conventional value chain is shown on the top left while the circle on the right represents the renting of garments which can be classified as a use-oriented product-service system according to [16]. PSS are defined as “a marketable set of products and services capable of jointly fulfilling a user´s need” [3]. According to [16, 17], PSS have the potential to lower the environmental impacts of consumption depending on the design of the business model and behavior of the users.

As mentioned before, assessing the environmental impacts of PSS presents a challenge as the scope of the study exceeds the typical stages of a products life cycle and to be able to derive whether the adaption of a rental PSS is less harmful to the

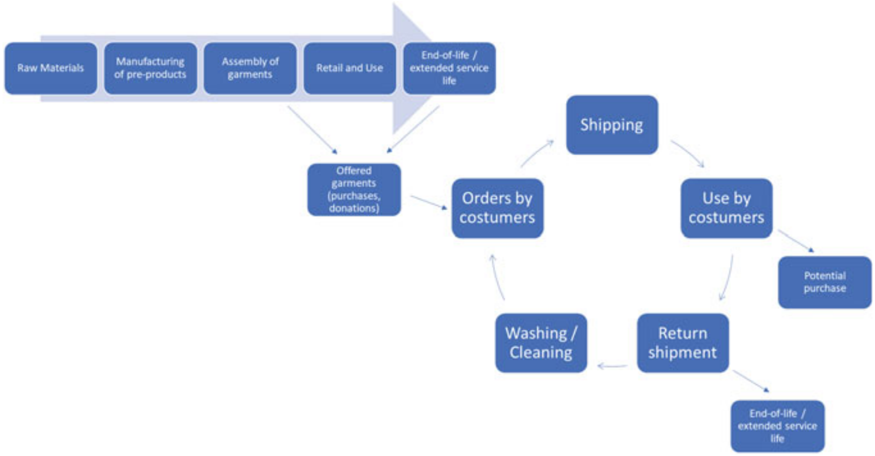


Fig. 1 Schematic diagram of the business model of rental wear (based on [12–14])

environment, different patterns of consumption instead of just two products have to be compared.

2 Challenges of Assessing the Environmental Impacts of a Product-Service System

Kjær et al. [9] point out that the assessment of the environmental impact of PSS using Life Cycle Assessment (described in ISO 14040 and ISO 14044) is challenging and also offering guidance on how to conduct a study [10]. According to the authors, the three main challenges applying LCA to a PSS are as follows:

– Identifying and defining the reference system.
– Defining the functional unit.
– Setting system boundaries.

While the more traditional application of attributional LCA is to assess the environmental impacts of one product over its life cycle from “cradle-to-grave” covering the conventional value chain (see Fig. 1 on the top left), the analysis of a PSS is more complex. It requires a broader view potentially covering various products and different activities, user behavior and the impact of the adaption of a PSS on the activities of the adopting users outside the direct use of the PSS.

The complexity starts at the beginning of the value chain. The global textile industry is vast and non-transparent. Raw materials, pre-products and garments are manufactured and shipped worldwide. Many pieces will never be used, and the total amount of garments manufactured and disposed is not publicly available and most likely unknown. During use, data collection presents a challenge as well. Especially regarding the consumption and use of garments, behavior and customs of people are varied and diverse. Regarding the disposal or prolonging of the life cycle of garments, fabrics and fibers, some data is available but might neglect a dark figure of stored, gifted or thrown away pieces.

To address those challenges and to offer one potential solution, a method to assess the environmental impacts of the adoption of a rental PSS for leisurewear from a consumer perspective was developed.

3 Approach: LCA of a PSS from a Consumer Perspective

A first version of the methodology was presented in Piontek et al. [12] before the approach was applied on a generic business model based on renting leisurewear to female consumers in Germany using the functional unit “One year of varied clothing (for a female consumer in Germany)”. The method allocates the environmental impacts of activities related to clothing consumption to one consumer. The production of the garments is allocated by considering the share of the lifetime of each garment if it is accessible by the consumer either because she owns it or because it was part of a parcel received from the rental company.

To cover the broad range of varieties described in the previous section, 54 scenarios have been composed of different blocks. The scheme is shown in Fig. 2.

Three types of consumers, based on the frequency of purchases and the time they use the garments, have been combined with their respective End-of-Life (EoL) scenarios. The baseline numbers are based on publications by Spiegel-Verlag [15], Greenpeace e.V. [4] and Geiger et al. [5]. Fashionistas are consumers who buy twice the number of garments and use them half of the time compared to the Baseline while conscious consumers are buying half of the clothing and using it for twice the amount of time.

At the EoL, the same amount of clothing as purchased (or the allocated amount for a rental model used during the reference year) is disposed by considering 55% of garments to be reused as second-hand garments (replacing garments), 35% reused as downcycled products (replacing primary fibers) and 10% of incineration. This might be highly different for other countries or depending on the quality of the garments as well as the way to dispose them chosen by the user.

For each consumer type, three modes of consumption have been considered: Conventional consumption and two versions of a monthly received parcel from a rental provider containing more basic clothes (like Shirts and pullovers, Rental 1) or the rental of more complex garments like a coat or dresses (Rental 2). Additionally,

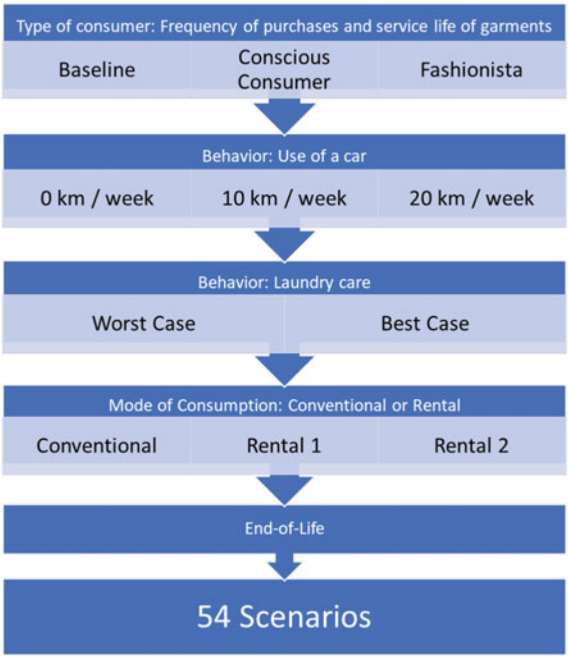


Fig. 2 Combination of scenarios I (based on [14] (CC BY 4.0, https://creativecommons.org/licenses/by/4.0))

two types of behavior have been considered: The mileage driven in a car related to the PSS (e.g., picking up a parcel from the post-office) or shopping activities and two scenarios for laundry care. The way the different behavioral patterns are combined is shown in Fig. 3. Every variation chosen influences one or more "blocks" of the reference flow. For example, the behavior during use is represented by one block for the use of a car and one block for laundry care. All blocks are summed to generate the combined reference flow of each scenario and finally the related environmental impacts.

Three examples for a scenario are as follows:

- A Baseline consumer, driving 10 km per week, worst case laundry care, having adopted rental scheme 1, disposing the respective garments at the end of their service life.
- A Conscious Consumer, driving 20 km per week, best case laundry care, buying clothing the conventional way, disposing the respective garments at the end of their service life.
- A fashionista, not using a car, best case laundry care, having adopted rental scheme 2, disposing the respective garments at the end of their service life.

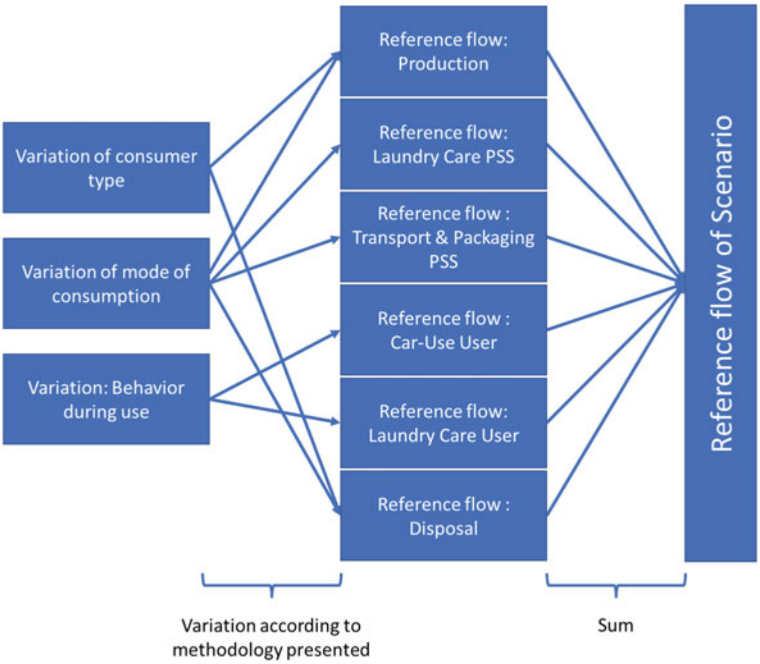


Fig. 3 Combination of scenarios II (based on [14] (CC BY 4.0, https://creativecommons.org/licenses/by/4.0))

The resulting 54 scenarios span a result space showing extremes and various combinations of behavior to allow for an analysis of hotspots and the derivations of findings. It may not be the case that a person finds herself in exactly one scenario or that a certain combination of "blocks" might seem reasonable for a certain group of people (e.g., consumers who despite being environmentally conscious, also driving a lot), but the result space should allow for the deduction of findings and the analysis of trends.

4 Findings, Recommendations and Limitations

Based on Life Cycle Inventories (LCI) for each scenario created using data from the GaBi databases provided by Sphera and a Life Cycle Impact Assessment (LCIA) using endpoint indicators from ReCiPe v1.1 (H), the matrix shown in Fig. 4 has been created.

At first glance at the matrices, it is obvious that a noteworthy reduction of environmental impacts only occurs for the user group "Fashionista". An adaption of a rental PSS can satisfy their need for access to different styles while reducing the environmental impacts compared to conventional consumption if the purchase of new garments is substituted by the adaption of the PSS. This is in line with the findings of other publications [8, 13, 18].

For a Baseline consumer, the adaption of the rental scheme offering more complex garments is linked to a slight reduction of environmental impacts for two out of three endpoint categories. For a conscious consumer, the environmental impacts are higher for nearly every impact category if compared to conventional (conscious) consumption.

An analysis at the midpoint level has shown that hotspots of the analysis in categories like global warming potential or particular matter formation are indeed also the use of a car as well as the energy consumption related to laundry care. Therefore, for users of rental PSS, it is recommended that they substitute the purchase of new garments by adapting a PSS and reflect on whether a subscription model is needed to satisfy their personal needs regarding the variety of clothing. The reduced usage of a combustion engine car as well as the optimization of the laundry care routine toward energy savings can also lower the personal impact on the environment.

If providers of rental clothing want to contribute to lower environmental impacts, they should address the right target group to avoid the rebound effect of incentivizing additional consumption and resource use. To replace the production of new garments, which is necessary to lower the overall impacts of consumption, the pieces offered by a rental provider should be long-lasting—both, in terms of technical life and fashion relevance. Additional offerings like style advice or the note that a customer can send the garments back without washing them before are options to strengthen customer satisfaction and lower environmental impacts. While not being assessed in a scenario, a flat rate offer, allowing a user to send back the parcels after even one

		Adaption of Rental 1		
		Damage to human health	Damage to ecosystems	Damage to resource availability
Baseline	0 km car , Worst Case laundry	Increase 0 – 10 %	Increase 0 – 10 %	Increase 0 – 10 %
	0 km car, Best Case laundry	Increase 0 – 10 %	Increase 0 – 10 %	Increase > 10 %
	10 km car, Worst Case laundry	Increase 0 – 10 %	Increase 0 – 10 %	Increase 0 – 10 %
	10 km car, Best Case laundry	Increase 0 – 10 %	Increase 0 – 10 %	Increase 0 – 10 %
	20 km car, Worst Case laundry	Increase 0 – 10 %	Increase 0 – 10 %	Increase 0 – 10 %
	20 km car, Best Case laundry	Increase 0 – 10 %	Increase 0 – 10 %	Increase 0 – 10 %
Cons. Con.	0 km car, Worst Case laundry	Reduction 0 – 5 %	Increase 0 – 10 %	Increase 0 – 10 %
	0 km car, Best Case laundry	Reduction 0 – 5 %	Increase 0 – 10 %	Increase > 10 %
	10 km car, Worst Case laundry	Reduction 0 – 5 %	Increase 0 – 10 %	Increase 0 – 10 %
	10 km car, Best Case laundry	Reduction 0 – 5 %	Increase 0 – 10 %	Increase 0 – 10 %
	20 km car, Worst Case laundry	Reduction 0 – 5 %	Increase 0 – 10 %	Increase 0 – 10 %
	20 km car, Best Case laundry	Reduction 0 – 5 %	Increase 0 – 10 %	Increase 0 – 10 %
Fashionista	0 km car, Worst Case laundry	Reduction > 10%	Reduction > 10%	Reduction 5 – 10 %
	0 km car, Best Case laundry	Reduction > 10%	Reduction > 10%	Reduction > 10%
	10 km car, Worst Case laundry	Reduction 5 – 10 %	Reduction 5 – 10 %	Reduction > 10%
	10 km car, Best Case laundry	Reduction > 10%	Reduction > 10%	Reduction 5 – 10 %
	20 km car, Worst Case laundry	Reduction 5 – 10 %	Reduction 5 – 10 %	Reduction 0 – 5 %
	20 km car, Best Case laundry	Reduction 5 – 10 %	Reduction > 10%	Reduction 0 – 5 %

		Adaption of Rental 2		
		Damage to human health	Damage to ecosystems	Damage to resource availability
Baseline	0 km car, Worst Case laundry	Reduction 0 – 5 %	Reduction 0 – 5 %	Increase 0 – 10 %
	0 km car, Best Case laundry	Reduction 5 – 10 %	Reduction 0 – 5 %	Increase 0 – 10 %
	10 km car, Worst Case laundry	Reduction 0 – 5 %	Reduction 0 – 5 %	Increase 0 – 10 %
	10 km car, Best Case laundry	Reduction 0 – 5 %	Reduction 0 – 5 %	Increase 0 – 10 %
	20 km car, Worst Case laundry	Reduction 0 – 5 %	Reduction 0 – 5 %	Increase 0 – 10 %
	20 km car, Best Case laundry	Reduction 0 – 5 %	Reduction 0 – 5 %	Increase 0 – 10 %
Cons. Con.	0 km car, Worst Case laundry	Increase 0 – 10 %	Increase 0 – 10 %	Increase 0 – 10 %
	0 km car, Best Case laundry	Increase 0 – 10 %	Increase 0 – 10 %	Increase > 10 %
	10 km car, Worst Case laundry	Increase 0 – 10 %	Increase 0 – 10 %	Increase 0 – 10 %
	10 km car, Best Case laundry	Increase 0 – 10 %	Increase 0 – 10 %	Increase 0 – 10 %
	20 km car, Worst Case laundry	Increase 0 – 10 %	Increase 0 – 10 %	Increase 0 – 10 %
	20 km car, Best Case laundry	Increase 0 – 10 %	Increase 0 – 10 %	Increase 0 – 10 %
Fashionista	0 km car, Worst Case laundry	Reduction > 10%	Reduction > 10%	Reduction 0 – 5 %
	0 km car, Best Case laundry	Reduction > 10%	Reduction > 10%	Reduction 5 – 10 %
	10 km car, Worst Case laundry	Reduction 5 – 10 %	Reduction 5 – 10 %	Reduction 0 – 5 %
	10 km car, Best Case laundry	Reduction > 10%	Reduction > 10%	Reduction 0 – 5 %
	20 km car, Worst Case laundry	Reduction 5 – 10 %	Reduction 5 – 10 %	Reduction 0 – 5 %
	20 km car, Best Case laundry	Reduction 5 – 10 %	Reduction 5 – 10 %	Reduction 0 – 5 %

Fig. 4 Result matrix (based on [14] (CC BY 4.0, https://creativecommons.org/licenses/by/4.0))

day, might lead to significant rebound effects due to transportation and cleaning of the garments.

The methodology and results presented are object to several limitations. The scenarios are based on selective data sources, as data on the production and use of clothing is not available in a high level of detail. As the environmental impacts are assessed from the point of view of a single female user in Germany, the results might be different for different countries and forms of the available rental offerings including different kinds of styles, garments and subscription models. Also, the impacts on the textile industry on a systemic level are out of the scope of the study.

5 Conclusion and Further Research

An LCA approach to assess rental business models has been presented. The emerging offering of renting leisurewear instead of buying, using and disposing garments in the conventional way has been chosen as the exemplary case study for the methodology. Findings from a result space opened up by 54 scenarios show that people who want to wear a broad range of different garments can lower their environmental footprint by adopting a rental model as long as the purchase of new garments is substituted. Others, especially conscious consumers might experience rebound effects linked to additional laundry care, transport and packaging linked to the rental scheme. Despite the consumption pattern, the change in the use of a combustion engine car and laundry care might have the potential to save environmental impacts.

For further research, the methodology could be adapted to other industries and goods like bikes, cars or tools available to be rented from DIY stores as well as outdoor equipment like tents and hiking backpacks. In the space of clothing, stationary rental offerings instead of online ones could be analyzed. A broader scope trying to include systemic changes using either consequential LCA or modeling methods like system dynamics could prove to lead to interesting findings as well.

References

1. Armstrong CM, Niinimäki K, Kujala S, Karell E, Lang C (2015) Sustainable product-service systems for clothing: exploring consumer perceptions of consumption alternatives in Finland. J Clean Prod 97:30–39
2. Fletcher K (2013) Sustainable fashion and textiles: design journeys. Routledge
3. Goedkoop MJ, Van Halen CJ, Te Riele HR, Rommens PJ (1999) Product service systems, ecological and economic basics. Report for Dutch Ministries of environment (VROM) and economic affairs (EZ) 36(1):1–122
4. Greenpeace EV (2015) Wegwerfware Kleidung
5. Geiger S, Iran S, Müller M (2017) Nachhaltiger Kleiderkonsum in Dietenheim. Ergebnisse einer repräsentativen Umfrage zum Kleiderkonsum in einer Kleinstadt im ländlichen Raum in Süddeutschland
6. Henninger CE, Amasawa E, Brydges T, Piontek FM (2022) My wardrobe in the cloud: an international comparison of fashion rental. In: Handbook of research on the platform economy and the evolution of e-commerce. IGI Global, pp 153–175
7. Iran S, Schrader U (2017) Collaborative fashion consumption and its environmental effects. J Fashion Market Manage Int J
8. Johnson E, Plepys A (2021) Product-service systems and sustainability: analyzing the environmental impacts of rental clothing. Sustainability 13(4):2118
9. Kjær LL, Pagoropoulos A, Schmidt JH, McAloone TC (2016) Challenges when evaluating product/service-systems through life cycle assessment. J Clean Prod 120:95–104
10. Kjær LL, Pigosso DC, McAloone TC, Birkved M (2018) Guidelines for evaluating the environmental performance of product/service-systems through life cycle assessment. J Clean Prod 190:666–678
11. Kozlowski A, Bardecki M, Searcy C (2012) Environmental impacts in the fashion industry: a life-cycle and stakeholder framework. J Corp Citizsh 45:17–36

12. Piontek FM, Rehberger M, Müller M (2019) Development of a functional unit for a product service system: one year of varied use of clothing. In: Progress in life cycle assessment. Springer, Cham, pp 99–104
13. Piontek FM, Amasawa E, Kimita K (2020) Environmental implication of casual wear rental services: case of Japan and Germany. Procedia CIRP 90:724–729
14. Piontek FM (2022) Ökobilanzierung von Product-Service Systems: Ein Beitrag anhand des Mietens von Freizeitkleidung. Doctoral dissertation, Ulm University, Ulm, Germany. Retrieved from https://oparu.uni-ulm.de/xmlui/handle/123456789/46571.
15. SPIEGEL-Verlag (2016) Outfit 9.0 Zielgruppen – Marken – Medien
16. Tukker A (2004) Eight types of product–service system: eight ways to sustainability? Experiences from SusProNet. Bus Strateg Environ 13(4):246–260
17. Tukker A (2015) Product services for a resource-efficient and circular economy: a review. J Clean Prod 97:76–91
18. Zamani B, Sandin G, Peters GM (2017) Life cycle assessment of clothing libraries: can collaborative consumption reduce the environmental impact of fast fashion? J Clean Prod 162:1368–1375

The Role of Country-Specific Gate-to-Gate Ecolabels: Case Study for Sri Lankan Clothing Industry

V. M. Jayasooriya and L. Ranasinghe

Abstract In the international trade, the textile and clothing production processes should comply with the local and international standards. In Sri Lanka, around 44% of textile and clothing products are exported mainly to Europe and the United States. Ecolabel is a tool that promotes a product or a service with reduced environmental impacts by considering its life cycle aspects. Ecolabels could be developed by considering various scopes such as cradle to grave, cradle to gate, gate-to-gate, or gate to grave phases in their life cycle. Moreover, there are several country-specific ecolabels available over the world especially for Asian counties such as Ecomark: India, Ecomark: Japan, and Korea Ecolabel. The textile export sector in these countries has significantly increased its market share by gaining customer reputation with respect to sustainable production and consumption, after the introduction of their own ecolabels. Currently, there are no ecolabels, developed particularly for Sri Lanka in relation to clothing industry which contributes for over fifty percent of the country's total exports. Currently, Sri Lanka is relying on ecolabels developed internationally. A unique ecolabel for Sri Lankan clothing industry is vital to compete with other countries in the international market as several Asian textile exporters are currently entering the market with their own ecolabels. Therefore, the major aim of this chapter is to introduce a framework for a potential gate-to-gate ecolabel for Sri Lanka backed by the experts in local apparel sector, considering the raw material storage to fabric manufacturing stages.

Keywords Ecolabel · Textiles · Gate-to-gate · Life cycle assessment · Apparel · Clothing industry

V. M. Jayasooriya (✉) · L. Ranasinghe
Department of Forestry and Environmental Science, University of Sri Jayewardenepura, Gangodawila, Nugegoda, Sri Lanka
e-mail: varuni.jayasooriya@sjp.ac.lk

S. S. Muthu (ed.), *Progress on Life Cycle Assessment in Textiles and Clothing*, Textile Science and Clothing Technology,
https://doi.org/10.1007/978-981-19-9634-4_6

1 Introduction

Clothing industry is known as garment industry, apparel industry, and/or fashion industry which covers the life chain of a cloth or a garment. However, clothing industry covers only the manufacturing of garments whereas the term apparel industry refers to the manufacturing of any manufactured material that is ready to be worn such as garments, footwear, and handbags. This chapter particularly focuses on Sri Lankan clothing sector, which is the highest contributing sector to the country's total exports annually. According to economists, nowadays, clothing industry has become one of the major contributors to the economy of majority of Asian countries. Similarly, in Sri Lanka, more than 15% of workforce is engaged in clothing industry [21]. Furthermore, Sri Lankan clothing industry designs and manufactures clothes and garments that are then distributed to the local and international market.

According to the Ecolabel Index [4], which is the largest global directory of ecolabels, there are 456 ecolabels in 199 countries and 25 industry sectors. Among these 456 ecolabels, 107 are ecolabels for the textile industry. Some of these ecolabels are unique ecolabels for one specific country such as Eco-Leaf, Ecomark: India, Ecomark: Japan, and Green Mark whereas some are adopted by many countries across the world. Some of the internationally renowned clothing industry ecolabels can be identified as Blue Angel, Green Seal, Nordic Swan, and EU Flower. The 'Blue Angle' ecolabel that is initiated by the German government is the oldest ecolabel in the world and it is applied to around 80 products including textiles [18].

In Sri Lanka, four ecolabels are currently applied for the sustainability assessment of clothing industry, which are 'Fairtrade, Global Organic Textile Standard (GOTS), IMO Certified and Naturland e.V.' [4]. Fairtrade incorporates social, environmental, and economic criteria-related requirements and terms of trade while GOTS ensures the organic status of textiles, in the harvesting stage of the raw materials. IMO certification is focused on natural textiles. Naturland e.V. is launched by Naturland association in order to promote organic textiles.

Majority of these ecolables only covers certain aspects of the life cycle which are mostly based on the raw materials. However, since approximately 95% of the raw materials required for the cloths are imported, these currently used ecolabels have limited applicability on the life cycle impacts on the manufacturing process that happens within the regional boundary of Sri Lanka. Therefore, this creates a need on focusing of developing a more focused ecolabeling framework for Sri Lanka, considering the gates that are operated within our regional boundary. Moreover, approximately over 50% of the end product is exported; it is difficult to track the life cycle impacts of these exported materials. Thus, the proposed framework in this chapter will cover limited life cycle stages, however, comprehensively associated within the gates of raw material storage to knitted–dyed fabric manufacturing.

In the modern society, the consumers have a fair knowledge and awareness about their responsibilities toward environment with the rising environmental threats due to industrialization. As customer decisions in product purchasing play a vital role in international market, industries, especially the clothing industry, tend to focus their production toward green or environmentally sustainable as much as possible. To achieve this objective, ecolabel can be considered as a key tool that proves the environmental friendliness of a product [2]. All ecolabels related to the environment are known as 'Environmental Labels' and ecolabel which mainly considers special criteria of comprehensiveness, independence and reliability could be identified as a subgroup of environmental labels. As per the Global Ecolabelling Network (2004) definition, an ecolabel is basically a label that identifies the overall environmental preference of a product or service based on lifecycle considerations. Generally, ecolabels evaluate specific product categories where a large range of alternatives are available such as textiles, food, appliances, electronics, cosmetics, etc. [24].

Furthermore, ecolabels provide an opportunity for consumers to select the most environmentally friendlier products and, therefore, local and international markets have shifted from manufacturing extensively harmful products to moderately or least harmful products. Therefore, as Sustainable Business Associates (2006) defined, ecolabeling is a voluntary method of environmental performance certification and an internationally accepted benchmark that is practiced around the world. Generally, ecolabels are largely based on the Life Cycle Assessment (LCA) which is known as a powerful environmental policy tool. As West [25] stated, ecolabels are associated with the concepts of eco-friendly, environmentally safe, recyclable, biodegradable, ozone-friendly, and low-energy-based manufacturing of the products.

Internationally accepted ecolabels are fast becoming a key component in Sri Lankan industrial sector in order to market the local export products by highlighting the sustainability and social welfare-related aspects. As stated earlier, Sri Lankan clothing industry is currently applying three ecolabels that are awarded by international organizations. Since the life cycle of a clothing product includes all the processes from raw material extraction, garment manufacturing to disposal of the garment, various boundaries could be associated during the ecolabel framework development. As discussed in forthcoming sections in this chapter, there are four types of ecolabels based on the above factors. They are cradle to grave, cradle to gate, gate to grave, and gate-to-gate ecolabels. Among these ecolabel types, considering the manufacturing process occurs within the local regional boundary, gate-to-gate ecolabel could be identified as a most suitable scope for the preliminary framework development for the Sri Lankan clothing industry.

In other words, this is the boundary that covers majority of the most significant processes of the life cycle of a garment as a greater damage can be imposed to the environment during its manufacturing phase. For an instance, significant amounts of wastewater, chemical, and dye effluent are generated during knitted-dyed fabric manufacturing from yarn.

In addition, the existing ecolabels are mostly developed by first world countries considering the manufacturing processes based on their advanced technology and potential resource availability. Therefore, different questions have been raised in applying these ecolabels in the Sri Lankan clothing industry as certain criteria and specific conditions cannot be achieved by Sri Lanka as a third world country with limited resources and associated technology. Hence, the integral framework of these internationally renowned ecolabels may not qualify to assess the sustainability of the overall garment production process to its full extent in Sri Lanka.

Correspondingly, this problem is valid for several other products especially for the export products. Therefore, Sri Lankan government has identified the need of developing unique ecolabels for different product categories including garments. Sri Lanka Standard Institution (SLSI), Sri Lanka Accreditation Board (SLAB), Ministry of Mahaweli Development and Environment, and Ministry of Science, Technology and Research have identified as key stakeholders in this process. The report entitled 'Recommendations for Eco-Labelling Platform for Sri Lanka' by Senaweera and Parasnis [19], submitted to the SWITCH-Asia SCP NPSC SL Project, highlights the need for unique labels for each of the individual product categories in Sri Lanka Furthermore, the stakeholders have recognized that there are some of the already developed ecolabeling frameworks in Sri Lanka for different industries which are not under operation due to poor recognition and support from Sri Lankan government.

Therefore, Sri Lankan government in collaboration with European Union currently seeking possibilities in developing potential ecolabels for a range of product categories. Thus, preliminary research such as the present work will provide guidance and support for such projects. In addition, the development of a unique ecolabel framework is highly important for the clothing sector which is one of the largest export economic markets in Sri Lanka.

Several Asian countries in the international export market currently promote their products through their own well-established ecolabeling programs. Some of the well-known examples are China, Japan, South Korea, Thailand, Singapore, and India. In recent years, there has been an increasing demand for these products in the international markets after introducing the country-specific ecolabels. Under these conditions, Sri Lanka has to enter the competition with the countries who are complying with these ecolabels, to maintain the expected product sustainability by international customers. Further to this, the numbers of certified products within such regions are going to get increased. Statistics of the Ministry of Finance, China, stated that after introducing country-specific ecolabels, the total volume of environmental labeled products in China reached 715.45 billion Yuan during 2008–2015 and it has supported opening China's international market for a range of additional products. It indicates that the region-specific and unique ecolabels contributed for the economy, sustainability, and social welfare in China. Hence, the ecolabels which are developed with own conditions of the country are significant in entering the international market against the world market competition.

According to the new regime of international trade agreements under World Trade Organization (WTO), the textile and clothing production processes should comply with the local and international environmental standards. If these standards are not followed precisely, Sri Lankan textile and clothing products would not be accepted by the international markets [7]. Since there is a considerable competition for clothing products in the international market, Sri Lankan cloths and garments may face difficulties without a country-specific ecolabel for the textile exports that assist the informed decision-making of consumers, even though they are of high quality, well-finished and sustainably manufactured.

During the last few decades, the environment has gone through an immense stress due to the industrial advancement across the world. Currently, this has become one of the most significant debates as it affects human well-being in both direct and indirect ways. Therefore, there is a global tendency that consumers are changing their attitudes toward practices such as sustainable consumption and production in order to maintain healthier environments for future generations. Consequently, the concept of 'green products' is increasingly recognized currently throughout the world. Under these circumstances, eco-friendly products have a high potential in the local and international markets as consumers always tend to buy eco-certified products though they are more expensive at the outset of sustainable consumption. Therefore, there is a need for Sri Lankan clothing industry to introduce a boundary specific ecolabel for the better performance of their products in the local and international markets. As explained earlier, the work presented in the chapter will offer an important insight for the ecolabeling in Sri Lankan clothing industry by providing a methodology to develop a framework for a potential ecolabel by identification of the criteria, indicators, and prioritization.

In summary, Sri Lanka as a developing country has a potential for both successes and failures of environmental and socio-economic conditions related to the clothing industry. Therefore, an ecolabel framework may be a fundamental component for maintaining environmental protection and socio-economic welfare during the manufacturing stages of a garment in Sri Lankan clothing industry. Therefore, it can be concluded that the development of an ecolabeling framework is a timely contribution to Sri Lankan clothing industry.

This chapter presents a novel systematic methodology performed for the development of a country-specific gate-to-gate textile ecolabel to assess the sustainability of apparels. The proposed framework mainly focuses on the life cycle stages of clothing manufacturing, which occurs within the regional boundary of the country. The methodology developed has been tested by applying it to the Sri Lankan apparel sector.

2 Sri Lankan Clothing Industry and Its Contribution to the Economy

In 1970s, Sri Lanka has shifted away from a socialist orientation and rapidly opened its economy to foreign investment [15]. Therefore, after 1977, the clothing industry started to play an important role in the Sri Lankan economy, and by 1986, it has become the largest export industry in Sri Lanka. Furthermore, since 1992, the clothing sector has become the largest net foreign exchange earner in Sri Lanka while accounting for 52% of total export earnings (USD 2,424 million) by 2002 [3].

However, during the last two decades, the clothing sector has achieved rapid and unbelievable growth. The major reason for this is the quota system that is introduced by Multi Fiber Arrangement (MFA) for exports of textiles and garment products to

Table 1 Garment export statistics in Sri Lanka (2012–2017)

	2012	2013	2014	2015	2016	2017
	US$. Mn	US$. Mn	US$. Mn	US$. Mn	US$. Mn	US$. Mn
Total exports	**1,896.0**	**1,897.0**	**2,317.0**	**2,308.0**	**2,413.8**	**2,281.0**
US	763.0	809.6	947.6	1,038.2	1,094.8	1,009.0
EU	943.0	871.6	1,098.3	990.8	1,008.5	953.0
Other	190.0	215.8	271.1	279.6	310.5	319.0

Source https://www.srilankaapparel.com/data-center/yearly-performance/

developed countries such as the US, EU, and Canada in order to assure international market access of developing countries like Sri Lanka which opened Sri Lankan economy for foreign investment.

As SLAEA [16] states, the percentage of exports from textiles accounted for 40% of the total exports, which accounts for 2% of the GDP of the country. SLAEA [17] further highlights that there is an increase of 46% of total exports while it accounts for 6% of the GDP of the country. Furthermore, around 40% of textiles are exported mainly to European (EU) countries and the US. In 2014, out of the total exports, 42% were exported to the US, 47% were exported to the EU, while the rest of 11% were exported to the other countries. Table 1 shows the export amounts of garments from January to June in past six years.

As Table 1 indicates, there is a decrease in exports of 2017 as the result of global downfall of the clothing industry due to increasing demand for low-cost garments by consumers. According to the Central Bank annual report, the highest contribution of Sri Lankan industrial exports in 2016 was from textiles and garments and it was US$ 4884 million in value. Clothing sector is one of the most significant economic contributors in Sri Lanka as it provides more than 1,000,000 of direct and indirect employments for Sri Lankans especially for rural people who have not completed their basic education. Major reason for higher economic contribution by Sri Lankan clothing industry is that famous internationally accepted branded clothes like Victoria's Secret, Liz Claiborne, Pierre Cardin, Abercrombie and Fitch, etc. are manufactured in Sri Lanka (The Island, 2002). These strong brands were already reached to the global level and they indicate the density and the future growth of the clothing industry in Sri Lanka.

There are more than thousand clothing industries in Sri Lanka and more than 500 among them are small-scale industries with less than ten employees. However, more than 65% of the industries are located near Colombo, the capital of Sri Lanka. Furthermore, with the development of the Sri Lankan clothing industry, various laws, acts, and regulations were implemented by the Board of Investment (BOI). On the other hand, a number of advantages are generated relating to Sri Lankan clothing industry through the establishment of Export Processing Zones (EPZ), strengthening local and international relationships among clothing industries, raw material suppliers and textile consumers, human resource development, technological advancement and developments in researches and innovations. However, Sri Lankan economy is shifted from agro-based economy to industrial economy with the rapid development of clothing sector.

2.1 Scope of the Sri Lankan Clothing Industry

When considering the scenario of Sri Lankan clothing industry, the majority of the raw materials such as cotton yarn and fabrics, other vegetable textile fibers, man-made filaments, other special woven fibers, chemicals, and dyes are imported. Annual report of the Central Bank [1] highlights that the value of imports of textiles and garment production accessories in the year was US$ 2,327.6 million. Therefore, in the first stage of the clothing life cycle, the raw material acquisition is not carried out within Sri Lankan regional boundary. Furthermore, as stated earlier, more than 40% of the end products of clothing industry such as garments and fabrics are exported every year. Some of the major textile export destinations of Sri Lanka are European countries, the US, Canada, and Japan. Among these countries, European countries and the US accounts for more than 88% of the total textile exports of Sri Lanka. Therefore, Sri Lankan clothing industry is confined to the scope of imported raw material storage to the exportation of end products when assessing the regional production sustainability.

3 Ecolabeling for Clothing Industry

Sustainable textile product is a product that is manufactured with the help of services and related materials in response to basic needs and bring a better quality of the life with the use of minimum amount of natural resources and toxic chemicals during the production, minimum waste emission to the environment over the life cycle of product keeping environmental and social factors in check throughout its supply chain [20]. Currently, understanding the customers 'willingness to purchase clothes that are made from sustainable raw materials with minimum scarce resource consumption is a complex issue [6]. Therefore, ecolabels are introduced to clothing industry to provide assistance in informed decision-making and to attract consumers by proving information regarding the sustainability of the garments that they purchase.

According to Ecolabel Index [4], there are 107 ecolabels that are used for the textile and clothing industry. Ecolabels such as ECOLOGO and Fair for Life consider both environmental and social criteria during the ecolabel development whereas certain ecolabels such as Blue Angle and Carbon Reduction Label consider only the environmental criteria. An ecolabel which is issued by a particular country may have developed the ecolabel based on their own technology and resource consumption concerns. Therefore, such certain ecolabels may not be suitable for direct application in other countries. In order to overcome this issue, many countries such as Taiwan, the

Philippines, Singapore, and India have attempted to uplift their clothing industries by introducing country-specific ecolabels.

Taiwan is one of the leading countries that elevated their clothing industry with a unique ecolabel named 'Green Mark' which was established in 1992. Market demand for Taiwan garments has increased rapidly due to the sustainability of Taiwan garments with the assistance of Green Mark ecolabel. After the establishment of Green Mark, Taiwan has become one of the 'Big Three' nations of Asian textile producers. There is high demand in Western European region and the US for the Taiwanese garments. According to Statista [22], from 2011 to 2018, the market value for Taiwanese garments has increased from USD 4 billion to USD 4.96 billion. Furthermore, by 1990, the value of US textile importation by Taiwan was USD 2,489 million. By 1997, it was reduced up to USD 2,166 million due to the improvement of sustainability and quality of Taiwanese garment sector [8].

Ecomark, which was established by Japan in 1989, considered the environmental impacts during the entire life cycle of clothes [4]. During 1990s, textile industrial districts were established with the rapid increase in demand for Japanese garments. The value of annual production was increased to more than 500 million Yen. However, clothing industry in Japan was succeeded within the distinct international market after the introduction of Ecomark label [26]. There was a significant increase in the market for girls' and women's clothes manufactured in Japan and the market volume for Japanese clothes has become approximately US$ 35,992 million by the year 2019 [23].

According to the Ecolabel Index [4], different environmental and/or social criteria are used by various ecolabels in European, US, Asian, Latin American, African, and Oceanic regions. Widely used environmental criteria by EU ecolabels are toxics, chemicals, natural resources, pesticides/herbicides/fungicides, material use, and energy whereas less focus was given on emissions, animal welfare, Genetically Modified Organisms (GMOs), and biodiversity by the majority of EU ecolabels. Work safety, worker health condition, fair trade, and community services are some of the social criteria used by EU ecolabels. Furthermore, toxics, chemicals, waste, material use, natural resources, and energy are some environmental criteria that are highly focused on by US ecolabels whereas fewer applications were found for the criteria of animal welfare, biodiversity, energy sources, and forests within these ecolabels. Even though the toxics, chemicals, material use, waste, and natural resources are highly focused by ecolabels in many other regions, less attention could be noted on criteria such as animal welfare, biodiversity, energy production, and emissions in US ecolabels.

3.1 Sri Lankan Context for Ecolabeling for Textile Industry

There are four ecolabels that are being applied in the Sri Lankan clothing industry which are Fairtrade, Global Organic Textile Standard (GOTS), IMO Certified, and

Naturland e.V. Basic information about these four ecolabels is shown in Table 2. Table 3 presents a SWOT analysis for the above four ecolabels.

Table 2 Ecolabels used in Sri Lankan clothing industry

Ecolabel	Logo	Used countries	Criteria	Scope
Fairtrade		Australia, Belgium, Brazil, China, Denmark, Germany, Japan, Hong Kong, Kuwait, New Zealand, Poland, South Africa, Sri Lanka, Sweden, Taiwan, Thailand, etc.	**Environment**—Biodiversity, energy use/efficiency, forests, GMOs, natural resources, pesticides/herbicides/fungicides, soil, toxics, waste, water use **Social**—Community services, cultural/indigenous/minority rights, diversity, fair trade, gender, housing/living conditions, human rights, labor relations/human resource policies, training and education, worker health condition, work safety, and other	Cradle to gate (mining/extraction to trade)
Global Organic Textile Standard (GOTS)		Australia, Bangladesh, Canada, China, Denmark, Egypt, Germany, Hong Kong, Italy, Japan, Malaysia, Pakistan, Sri Lanka, Thailand, Taiwan, US, United Kingdom (UK), etc.	**Environmental**—Chemicals, GMOs, Material use, natural resources, pesticides/herbicides/fungicides, soil, toxics, wastewater/sewage, water quality **Social**—Cultural/indigenous/minority rights, gender, human rights, labor relations/human resource policies, training and education, worker health condition, work safety	Gate-to-gate (commodity production to consumer use)

(continued)

Table 2 (continued)

Ecolabel	Logo	Used countries	Criteria	Scope
IMO certified		Algeria, Bangladesh, Brazil, Chile, China, Indonesia, Ireland, Japan, Nepal, South Africa, Sri Lanka, Switzerland, Thailand, Taiwan, US, UK, etc.	**Environment**—Chemicals, forests, pesticides/herbicides/fungicides, soil, toxics	Gate to grave (product processing and product recovery/recycling)
Naturland e.V.		Germany, Mexico, Sri Lanka	**Environmental**—Animal welfare, biodiversity, chemicals, forests, GMOs, natural resources, pesticides/herbicides/fungicides, soil, toxics **Social**—Community services, cultural/indigenous/minority right, fair trade, gender, human rights, labor relations/human resource policies, training and education, worker health condition, work safety	Gate-to-gate (processing)

Source Ecolabel Index [4]

4 Need for a Country-Specific Ecolabel

As per the above review, Sri Lankan clothing industry currently applies four ecolabels for the exported garments since these ecolabels are awarded by internationally accepted organizations. According to the SWOT analysis given in Table 3, it is evident that the currently used four ecolabels in Sri Lankan clothing industry are not completely suitable for Sri Lankan context. Furthermore, the different weights that has been given to these ecolabels might not be completely suitable to Sri Lanka considering the different types of machinery, fuel, and other processes that are applied in Sri Lanka. Therefore, at present, Sri Lankan industrial sector has identified the need for a country-specific ecolabel not only for the clothing industry but also for all the export products.

However, there is no credible and nationally accepted framework for ecolabels in Sri Lanka in order to attract the consumers toward sustainable export products that are manufactured locally. Under this situation, developing a unique ecolabeling

Table 3 SWOT analysis of existing Sri Lankan clothing industry ecolabels

Ecolabel	Strengths	Weaknesses	Opportunities	Threats
Fairtrade	Both environmental and social criteria were considered Accredited by an independent third-party certification body	A cradle to gate ecolabel and not completely suitable for the scope of the Sri Lankan clothing industry	High awareness about the ecolabel as it is widely spread among all regions During the ecolabeling development, energy, waste, and water which are highly significant in the Sri Lankan clothing industry were highly concerned	Most of the criteria like biodiversity, forests, GMOs, pesticides/herbicides/fungicides are not suitable for Sri Lankan clothing industry, and most suitable criteria for Sri Lankan context like emissions and chemicals are not concerned during the ecolabeling development
GOTS	Both environmental and social criteria were considered Accredited by an independent third-party certification body	Though GOTS considers about gate-to-gate approach, not completely suitable for the scope of the Sri Lankan clothing industry as it is considered the stage of consumer use	High awareness about the ecolabel as it is widely spread among all regions Energy, wastewater, water quality, etc. which are highly significant in the Sri Lankan clothing industry were highly concerned	Most of the criteria like soil, GMOs, pesticides/herbicides/fungicides are not suitable for the Sri Lankan clothing industry and most suitable criteria for Sri Lankan context like emissions are not concerned during the ecolabeling development
IMO certified	Accredited by an independent third-party certification body	Only environmental criteria were considered Scope of the ecolabel is not completely matched with the scope of the Sri Lankan clothing industry	High awareness about the ecolabel as it is widely spread among many regions	Most criteria except chemicals and toxics are not related to the scope of the Sri Lankan clothing industry Energy, water use, wastewater, and emissions which are highly important to Sri Lankan clothing industry were not concerned through the ecolabel

(continued)

Table 3 (continued)

Ecolabel	Strengths	Weaknesses	Opportunities	Threats
Naturland e.V.	Both environmental and social criteria were considered Scope of ecolabel is suitable for Sri Lankan ecolabel	Less awareness about the ecolabel as only expand in a few countries	Toxics and chemicals were highly concerned	Most of the criteria like animal welfare, GMOs, forests, and natural resources are not suitable for the scope of Sri Lankan clothing industry Energy, water use, wastewater, and emissions which are most important for Sri Lankan clothing industry were not considered during ecolabeling development

Source Ecolabel Index [4]

framework for Sri Lankan clothing industry by considering a country-specific scope is very much significant to maintain the demand for the local export products in the international market [19].

4.1 Scope of the Ecolabeling Framework

Studying the local situation of the Sri Lankan clothing industry is important when identifying the most suitable scope for an ecolabeling framework. As already discussed, there are four types of ecolabels based on the scope of the ecolabel as cradle to grave, cradle to gate, gate to grave and gate-to-gate ecolabels.

Since Sri Lanka imports more than 95% of raw materials that are required for clothing industry, majority of raw materials are not manufactured in Sri Lanka. Furthermore, more than 40% of output from Sri Lankan clothing industries is exported. Therefore, it is difficult to track down all the processes within the clothing production life cycle from cradle to grave as various phases could be associated with various regions throughout the world.

Therefore, when identifying the scope of an ecolabeling framework for Sri Lanka, it is important to identify suitable gates that operate within Sri Lanka, to define and evaluate region specific criteria and indicators. As the majority of the raw materials are imported and the finished clothing products are exported, a 'gate-to-gate' ecolabeling framework which includes life cycle phases that are operated within the regional boundary was considered during this study.

Within the scope of the 'gate-to-gate', 'Yarn storage to knitted-dyed fabric manufacturing' phases were considered as the system boundary of the proposed ecolabel in the present work since most of the negative environmental impacts are occurred during these life cycle phases for the clothing industry which are operated within our regional boundary. Therefore, the scope of the present ecolabeling framework lies within the yarn storage to fabric manufacturing phases. However, the methodology discussed in this chapter could be further extended for the assessment of further life cycle phases of the apparel sector, in the future.

Different phases of the life cycle of a product are considered in the development of an ecolabeling framework. Accordingly, there are four types of ecolabels that could be defined. They are cradle to grave, cradle to gate, gate to grave, and gate-to-gate ecolabels. Based on a stakeholder consultation within local apparel sector, a scope that is suitable for an ecolabeling framework that can be applied to Sri Lankan clothing industry was identified. Major intention of this work was to identify the most suitable criteria for an ecolabel which could be applied with the processes that occur within the regional boundary of Sri Lanka.

4.2 Methodology Applied

Methodology of this research was developed mainly based on the criteria development procedures used in EU and US textile ecolabels especially 'Blue Angel' and 'Hong Kong labeling system'. 'Blue Angle' ecolabel was initiated by the German government while the Hong Kong labeling system was launched by Hong Kong Green Council [9]. 'Blue Angle' is one of the specific ecolabels which is commonly used by all regions such as the US, EU, Asia, Africa, and Oceania. Hong Kong ecolabel is a unique ecolabel for the Hong Kong region that is developed by considering the suitability criteria for an Asian region. Figure 1 shows the steps followed for the development of the ecolabeling framework in the present study.

4.2.1 Identification of the Initial Criteria and Indicators for the Ecolabel

An extensive literature review was initially carried out to identify the most important criteria and indicators that would be applicable for an ecolabel in Sri Lanka. Major sources for the review of ecolabels for this study was the 'Ecolabel Index' and the Global Ecolabelling Network (GEN). Ecolabel Index is the largest international database that is solely dedicated for the Ecolabels [4]. Furthermore, LCA reports related to clothing industries were reviewed to identify the criteria and indicators which has the highest environmental impacts during the textile manufacturing life cycle.

For the initial shortlisting, the ecolabels applied in the EU and the US were considered to assess the criteria and indicators for the label, as the majority (more than 40%) of Sri Lankan clothes and fabrics are exported to these countries. In addition to these two regions, the ecolabels applied in Asian region were considered to identify particular criteria and indicators that are most applicable for the countries in the same region. According to the Ecolabel Index database, among 107 textile ecolabels in the world, there are 55 EU textile ecolabels, 55 US textile ecolabels, and 41 Asian ecolabels. Among Asian ecolabels, three ecolabels are currently applied in

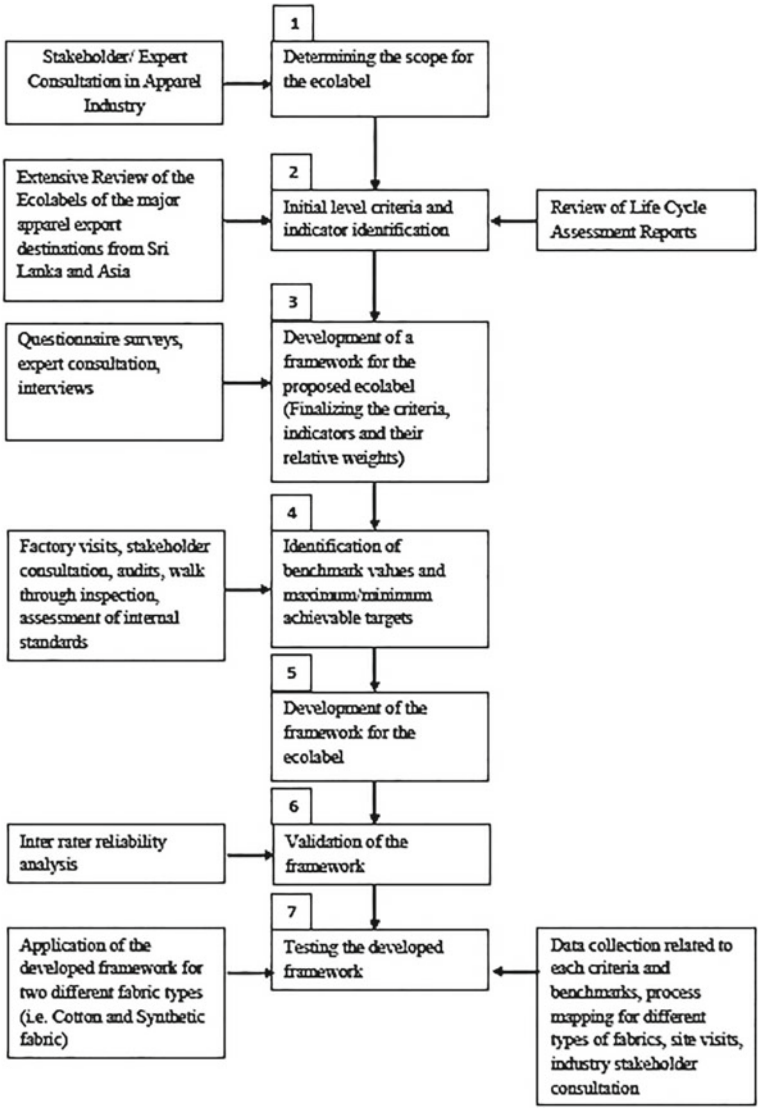


Fig. 1 Methodology for the development of ecolabelling framework

Sri Lanka as mentioned before. Based on the review of the ecolabels, commonly used criteria and the indicators were identified which are used within the gates considered. It should be noted that, for the development of the present framework for the ecolabel, only the criteria related to the environmental aspect have been considered. No social considerations were assessed for the current framework.

4.2.2 Expert Preference Elicitation to Obtain the Relative Weights for Criteria and Indicators

The major intention of this step was to verify the identified criteria and indicators, to finalize them, and to allocate relative weights for each of the criteria and indicators. After identifying criteria and indicators which are used in EU, US, and Asian ecolabels, a framework for the proposed ecolabel was drafted. There were two major components considered under this framework. Those were the major criteria of interest and the indicators that could be used to evaluate these criteria. There were one or more indicators under each and every criterion.

Based on expert consultations and interviews, criteria and indicators were finalized. Then a questionnaire survey was carried out by selecting experts in the Sri Lanka clothing industry who were grouped under three major categories as top management, plant/sustainability managers, and team members and stakeholders in research and development (e.g., academics, researchers) to obtain relative weights for the criteria and indicators.

As Jha [11] has stated, by 2018, more than a thousand clothing industries are scattered over Sri Lanka which provide employment opportunity for more than 300,000 men and women, and among these industries, there are around 350 factories that contribute for export of garments in a significant level. Not only export garments but also locally used garments are manufactured in Sri Lankan clothing sector. Furthermore, Sri Lankan clothing industry can be classified under small, medium, and large scale and the most significant factor is that there are around 70 large-scale clothing industries. As already stated, according to SLAEA [17], top large-scale export clothing industries are Brandix Apparel Ltd., MAS Intimates Pvt. Ltd., Hirdaramani International Exporters Pvt. Ltd., MAS Active Trading Pvt. Ltd., Bodyline Pvt. Ltd., Smarts Shirts Lanka Ltd., and Omega Line Ltd.

Brandix Apparel Ltd. is the largest exporter of garments in Sri Lanka, and it is a group of garment factories that is comprised of around eight companies, while MAS group is the largest apparel and textile manufacturer in South Asia who manages the business with revenue of US$1.8 billion over the world. Likewise, as Jha [11] stated, Sri Lankan clothing industry is accounted for 1.2% of the market share in the global garment industry. As the complexity of the large-scale industries, there are several industrial plants under each and every large-scale industry.

The respondents for the questionnaire were selected by considering the above factors who represent various textile exporting organizations in Sri Lanka (especially the large-scale manufacturers) and also the stakeholders from external entities such as academics in the field who were categorized under three groups as discussed in the forthcoming sections. Sample size of this research was 43 while 10 respondents were from top management level, 20 respondents were plant/sustainability managers and team members and 13 respondents were stakeholders in research, innovation, and standards development.

Top management consisting of a chairman, General Managers (GM), senior executives, and deputy managers is the backbone of the clothing industry due to their experience, perceptions, and motivation to drive an industry forward or backward.

They must have a clear image about the industry, its processes, and the negative and positive impacts of its activities. Furthermore, they also have the responsibility to implement sustainable initiatives.

The other category identified was plant/sustainability managers and team members consisted of plant managers, sustainable directors, sustainable executives, and quality assurance officers. Plant managers in the clothing industry play an important role in giving leadership for the employees to achieve their targets. An industrial plant is handled according to the demands handled by the plant manager. It means the majority of tasks are operated according to the orders of the plant manager. Therefore, plant managers were taken into account when selecting the sample. Accordingly, sustainability managers and sustainability executives are responsible for implementing sustainable initiatives and leading their employees toward achieving the company's environmental policy and targets during manufacturing while focusing on reduction of negative environmental impacts that occur within the organizational boundary.

Furthermore, engineering professionals, academics, and research and innovation managers who are engaged in the environment and clothing industry were categorized under the next stakeholder category. Environment and clothing industry-related engineers such as environmental engineers and chemical engineers provide assistance for environment protection innovations by considering energy efficiency, water efficiency, and Carbon footprint reduction in order for the companies to move toward sustainability alongside the technological advancement.

Likewise, environment and clothing industry-related academics play one of the major roles in the clothing industry though are not directly involved in the operations with the industry. They provide guidance for the clothing industries to achieve their aims while giving necessary instructions through different assessments and awareness programs to reduce negative environmental impacts. In addition, another important factor is that academics guide their undergraduates who may join with clothing industry in near future by giving them awareness on the linkage between the clothing industry and the environment. However, particularly, based on the position of the industry, role inside the clothing industry, and knowledge to strengthen the linkage between the clothing industry and the environment, the respondents were selected for the questionnaire survey.

Questionnaire survey

An online questionnaire survey was developed using Qualtrics software for weight elicitation for the stakeholders in the Sri Lankan clothing industry. The SWING weighting method was used for obtaining the weights for each criterion and indicator. The objective of the questionnaire survey was to study the perception of the different stakeholders relating to the Sri Lankan clothing industry in criteria prioritization and allocation of the relative weights for each of the criteria. Points were to be allocated for each criterion based on their importance in producing an eco-friendly textile product. Respondents were asked to rate the criteria based on the importance of producing an eco-friendly textile product. At first, they were asked to identify the most important criteria based on their view and give it a rating of 100 using the sliding bar. Next, they were asked to rate each of the other criteria in turn on a scale of 0–99, to indicate how important they would be compared to the most important criterion in their decision. At the same time, the respondents were asked to rate the indicators. The score of the least important criterion may not be zero.

Results of the online questionnaire survey were analyzed to identify the relative importance of each criteria and indicators. The percentage weights of criteria and indicators for each respondent were calculated. Then mean values and median values of percentage weights were calculated for each and every criterion and indicator. Based on those values, points were allocated for each criterion and indicator. The points were given out of 100 were normalized for a score of 100. To obtain a single representative weight for the criteria and indicators, different methods can be used such as mean or median. In this study, median weight was used as the representative weight as the median has proven to be the measure that agrees well with the majority of the views of the group in decision-making [13, 10]. Furthermore, median has also been identified as not as sensitive as mean on extreme values [12]. Due to these advantages, median value has taken as the measure of representing the view of the expert panel on weight elicitation over the mean value.

4.2.3 Identification of Benchmark Values and Maximum/Minimum Achievable Targets

Benchmark values and maximum/minimum achievable targets were identified for every indicator. Benchmark values and maximum/minimum achievable targets were developed based on factory visits, stakeholder consultation, preliminary audits, walk-through inspections, and assessment of internal standards. The major intention of this step was to develop benchmark values and maximum/minimum achievable targets under each indicator and to allocate points according to their importance in achieving each criterion and indicator.

4.2.4 Development of the Final Framework for the Ecolabel

All criteria, indicators, benchmark values, and maximum/minimum achievable targets and points for each of these according to their importance were finalized. The major intention of this step was to finalize the proposed framework for the ecolabel and to present the final rating system with the complete framework.

4.2.5 Validation of the Framework

Inter-rater reliability testing was carried out for the validation of developed ecolabeling framework. Both criteria and indicators were validated. There, the degree of consensus and reliability of both criteria and indicators were measured. Two types of indicators were used to validate the framework. Those were Intraclass Correlation

Table 4 Ranges for the degree of consensus

Range	Response
$0 < CV \leq 0.5$	Good degree of consensus
$0.5 < CV \leq 0.8$	Less than the satisfactory degree of consensus
$CV > 0.8$	Poor degree of consensus

Source English and Kernan [5]

Table 5 Ranges of reliability for ICC

Range	Response
<0.5	Poor reliability
0.5–0.75	Moderate reliability
0.75–0.9	Good reliability
>0.9	Excellent reliability

Source Koo and Li [14]

Coefficient (ICC) and co-efficient of variation. ICC was calculated by SPSS in order to assess the inter-rater reliability for the weights obtained for criteria and indicators. Furthermore, co-efficient of variation was calculated for criteria and indicators separately in order to identify the degree of consensus among respondents in weighting each criterion and indicator of the framework.

Assessment of the degree of consensus of the experts on the proposed ecolabeling criteria and indicators

Coefficient of variation was used as the indicator of assessing the degree of consensus of the group of experts for each criterion and indicator of the framework. This was analyzed against the standard values which depict the degree of consensus in group decision-making as shown in Table 4.

Assessment of the inter-rater reliability

Intraclass Correlation Coefficient (ICC) was used to identify the degree of reliability of the stakeholders among each criterion and indicator. ICC for both criteria and indicators were calculated by using SPSS and compared with the standard ranges of reliability for ICC as shown in Table 5.

5 Ecolabeling Framework Proposed for Sri Lanka

5.1 Determining the Scope for the Ecolabel

As identified earlier, the most suitable scope for Sri Lankan clothing industry is 'Gate-to-gate'. Due to the complexity of gate-to-gate scope within the clothing industry

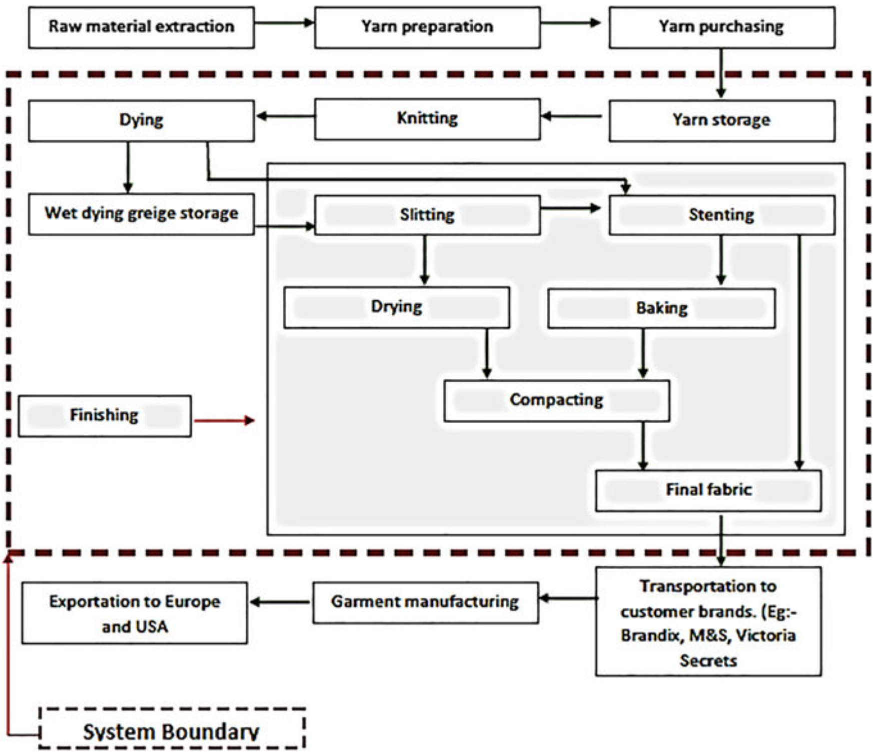


Fig. 2 Process flow chart of the knitted-dyed fabric based clothing industry

being broad with including a number of different processes. 'Yarn storage to knitted-dyed fabric manufacturing' phases were considered as the system boundary of this research. The process flow chart of the clothing industry is shown in Fig. 2 and the process flow chart of the considered system boundary is shown in Fig. 3.

As shown in Fig. 2, the processes in gray color box are called as finishing processes and one or more processes in gray color box are needed to finish the knitted-dyed fabric manufacturing. No. of finishing processes are depending on the fabric type.

5.2 Identification of the Initial Criteria and Indicators for the Ecolabel

Among the 107 textile ecolabels which are already available, 55 European ecolabels, 55 US ecolabels, and 41 Asian ecolabels were reviewed. Based on the results of extensive review, criteria, and indicators that are used in European, US, and Asian ecolabels were summarized. Figures 4, 5, and 6 show the graphical analysis of criteria and indicators that are used by European, US, and Asian ecolabels, respectively.

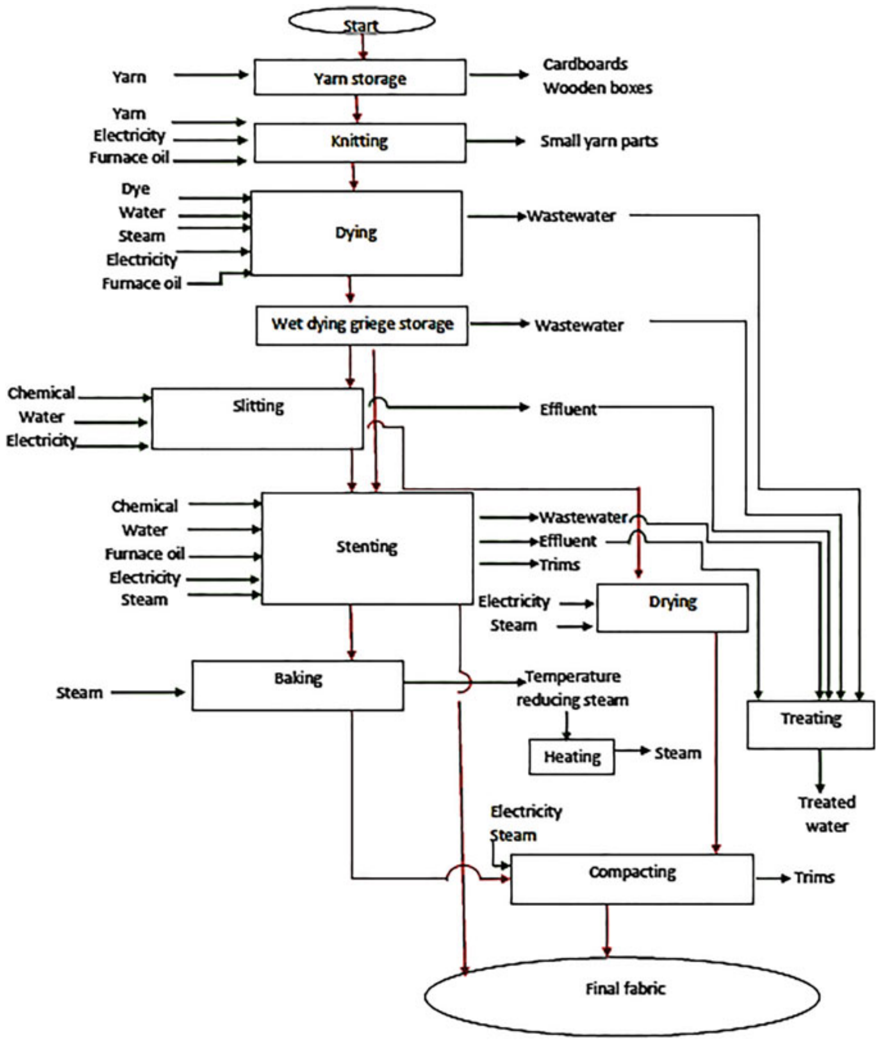


Fig. 3 Process flow chart of the considered system boundary in knitted-dyed fabric-based clothing industry

Consequently, 20 common criteria were identified through the reviewing of 55 EU, 55 US, and 41 Asian ecolabels. The top 5 criteria used in EU ecolabels were toxics, chemicals, natural resources, pesticides/herbicides/fungicides, and material use. Furthermore, toxics, chemicals, material use, waste, and natural resources are the widely used criteria in US ecolabels while Asian ecolabels are focused on toxics, material use, natural resources, waste, and energy use/efficiency as their major criteria.

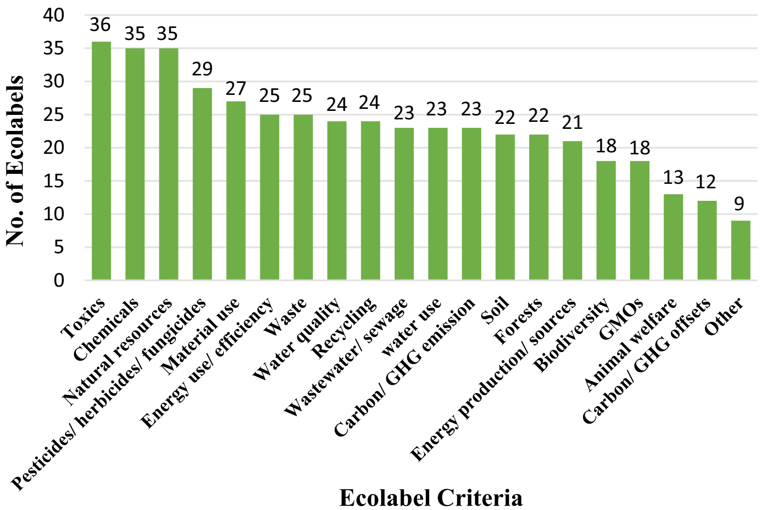


Fig. 4 Number of ecolabels versus criteria—European ecolabels

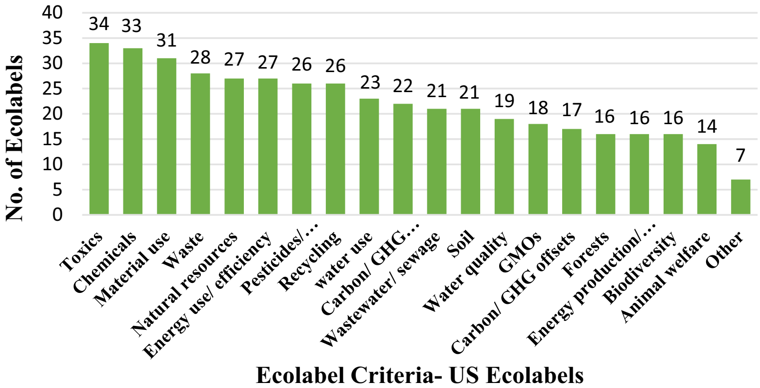


Fig. 5 Number of ecolabels versus criteria

5.3 Expert Preference Elicitation to Obtain the Relative Weights for the Criteria and Indicators

While proposing a framework for the ecolabel based on the review, 6 criteria were identified suitable for developing an ecolabeling framework for Sri Lankan clothing industry. One or more indicators under each criterion were identified.

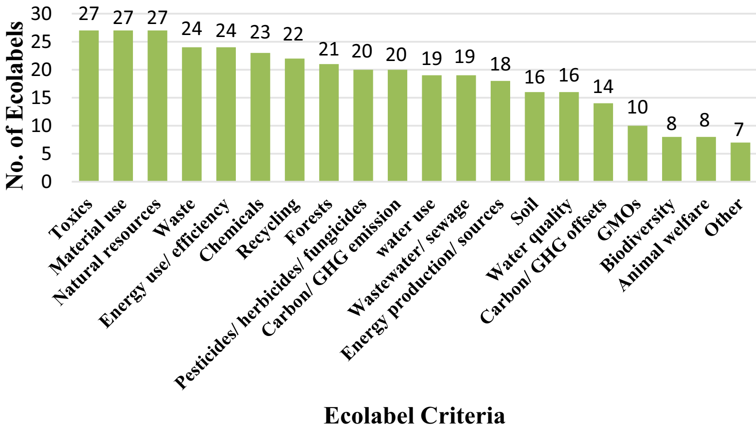


Fig. 6 Number of ecolabels versus criteria—Asian ecolabels

5.3.1 Questionnaire Survey

The sample size of the questionnaire survey was 43 and the sample consisted of different stakeholders related to clothing industry. The respondents were classified into five categories as shown in Table 6. All respondents were asked to allocate points for each criterion and indicator according to their view by following the given instructions. Table 7 shows the selected criteria and indicators for Sri Lankan clothing industry ecolabel framework.

Based on the mean value of the weights, points were allocated for each of the criteria of the framework to generate 100 as the total sum of points. Furthermore, points for indicators were calculated by using mean values of percentage values of results from the questionnaire.

Table 6 Classification of respondents of the questionnaire survey

Group	No. of respondents
Top management	10
Plant/sustainability managers and team members	20
Academics/Stakeholders in textile research, innovation, and standard development	13
Total	**43**

Table 7 Selected criteria and indicators for the ecolabeling framework

Criteria	Indicators
Sustainable chemical management practices	Minimizing restricted/hazardous chemicals
	Best practices in chemical storage and handling
Usage of sustainable materials	Usage of organic materials
	Usage of reusable/recyclable materials
Energy conservation and management	Reducing overall energy intensity
	Increasing renewable energy usage
Water, wastewater, and effluent management	Reducing the overall water intensity
	Enhancing the water reuse
	Industrial wastewater management
Solid waste management	Management of industrial (non-hazardous) solid waste
	Management of hazardous waste
	Management of general waste
Green House Gas (GHG)/Carbon emission management	Measures for the Reduction of GHG Emissions

5.4 *Identification of Benchmark Values and Maximum/Minimum Achievable Targets*

Benchmark values and maximum/minimum achievable targets were identified under each indicator and points were allocated for each and every benchmark value and maximum/minimum achievable target according to their importance in achieving each criterion and indicator. The benchmark values and maximum/minimum achievable targets were developed through factory visits, stakeholder consultation, preliminary audits, walk through inspection, and the assessment of internal standards. Based on the aforementioned studies, several prerequisites were identified as the mandatory requirements for the ecolabeling framework. The prerequisites, identified in the framework are shown in Table 8. According to prerequisite 01, it is important to have an established Environmental Management System within the organization to ensure that the company's commitment to environmental protection and its conformance with related legislation. Moreover, as prerequisite 02, clothing industries should use properly certified raw materials in order to continue the environmental friendliness of a garment throughout the life cycle chain.

Table 8 Finalized ecolabel framework for Sri Lankan clothing industry

Ecolabeling framework		
Clothing industry—from yarn storage to fabric manufacturing		
	Description	Points
Prerequisite 01	Manufacturing organization should be certified with ISO 14001:2015 Environmental Management Systems (EMS)	
Prerequisite 02	Raw materials for the fabric manufacturing must be certified by an accredited certification body	
Prerequisite 03	Appointment of one or more qualified personal responsible to industry's compliance with applicable ecolabel criteria system (number of people may depend on the size and the complexity of the industry, i.e., number of plants and their geographical locations)	
Criterion 01	***Sustainable chemical management practices***	***18***
Indicator 01	**Minimizing the restricted/hazardous chemicals**	
Benchmark values and maximum/minimum achievable targets	Zero usage of restricted/hazardous chemicals used including ZDHC and customer positive list	6
	Conducting hazardous chemical awareness programs/workshops (at least once a year)	2
	Application of the principles of green chemistry during the manufacturing process (within the gates considered in the ecolabel)	2
	Subtotal	**10**
Indicator 02	**Best practices in chemical storage and handling**	
Benchmark values and maximum/minimum achievable targets	Maintaining safety data sheet (SDS) in chemical storage and handling	4
	Exhibiting clear instructions for chemical storage and handling in chemical storages and usage places	2
	Regular (at least once a year) training program for chemical storage and handling and up-to-date training program records	1
	Maintaining an up-to-date database on the release and storage of chemicals and their quantities	1
	Subtotal	**8**

(continued)

Table 8 (continued)

Ecolabeling framework		
Clothing industry—from yarn storage to fabric manufacturing		
	Description	Points
Criterion 02	***Usage of sustainable materials***	***15***
Indicator 01	**Usage of organic materials**	
Benchmark values and maximum/minimum achievable targets	Percentage of organic materials used during the processes (out of total raw materials) (maximum allowable point is 6)	
	Organic material content = 100%	6
	50% ≤ organic material content < 100%	3
	40% ≤ organic material content < 50%	1
	Maintaining separate records for the organic raw material usage and their composition	2
	Subtotal	**8**
Indicator 02	**Usage of reusable/recyclable materials**	
Benchmark values and maximum/minimum achievable targets	Type of materials (maximum allowable point is 5)	
	Using only reusable/recyclable raw materials during the processes	5
	Using both reusable/recyclable and non-reusable materials during the processes	2
	Comparison records including evidence of increasing reusing or recycling materials throughout the processes (within the gates) (at least for the last 2 years)	2
	Subtotal	**7**
Criterion 03	***Energy conservation and management***	***16***
Indicator 01	**Reducing overall energy intensity**	
Benchmark values and maximum/minimum achievable targets	Percentage reduction of energy intensity from the internal monthly target value (maximum allowable point is 6)	
	Reduction of energy intensity ≥ 10%	6
	8% ≤ Reduction of energy intensity < 10%	4
	6% ≤ Reduction of energy intensity < 8%	2

(continued)

5.5 *Development of the Final Framework for the Ecolabel*

Final rating scheme for the ecolabeling framework for Sri Lankan clothing industry shows in Table 9. All criteria, indicators, benchmark values, and maximum/minimum achievable targets and points for each of them were finalized as shown in Table 8.

Table 8 (continued)

Ecolabeling framework		
Clothing industry—from yarn storage to fabric manufacturing		
	Description	Points
	4% ≤ Reduction of energy intensity < 6%	1
	Application of innovative technologies/alteration of technologies for the reduction of energy intensity	2
	Subtotal	**8**
Indicator 02	**Increasing renewable energy usage**	
Benchmark values and maximum/minimum achievable targets	Percentage use of renewable energy out of the total energy consumption (maximum allowable point is 8)	
	Percentage use of renewable energy < 50%	8
	30% ≤ Percentage use of renewable energy ≤ 50%	4
	Subtotal	**8**
Criterion 04	***Water, wastewater, and effluent management***	***19***
Indicator 01	Reducing the overall water intensity	
Benchmark values and maximum/minimum achievable targets	Percentage reduction of water intensity out of the internal monthly target value (maximum allowable point is 4)	
	Percentage reduction of water intensity < 5%	4
	3% ≤ Percentage reduction of water intensity ≤ 5%	2
	Application of innovative technologies/alteration of technologies to reduce the overall water intensity	2
	Subtotal	**6**
Indicator 02	**Enhancing the water reuse**	
Benchmark values and maximum/minimum achievable targets	Percentage of water reuse from the total water consumption (maximum allowable point is 6)	
	Water reused percentage > 50%	6

(continued)

Table 8 (continued)

Ecolabeling framework		
Clothing industry—from yarn storage to fabric manufacturing		
	Description	Points
	30% ≤ water reused percentage ≤ 50%	2
	Subtotal	**6**
Indicator 03	**Industrial wastewater and effluent management**	
Benchmark values and maximum/minimum achievable targets	Presence of zero hazardous substances in the wastewater and effluent	3
	Having a regularly operated internal wastewater and effluent treatment plant	2
	Separate internal unit for wastewater testing	1
	Innovation related to industrial wastewater and effluent management	1
	Subtotal	**7**
Criterion 05	***Solid waste management***	***15***
Indicator 01	**Management of industrial (non-hazardous) solid waste**	
Benchmark values and maximum/minimum achievable targets	Internal/external reuse of all non-hazardous solid waste	3
	Maintaining an up-to-date database for the composition of non-hazardous solid waste and quantities generated and the end use	2
	Subtotal	**5**
Indicator 02	**Management of hazardous solid waste**	
Benchmark values and maximum/minimum achievable targets	Zero hazardous solid waste generation	3
	Continuous program for the monitoring of hazardous solid waste and their disposal	2
	Subtotal	**5**
Indicator 03	**Management of general waste**	
Benchmark values and maximum/minimum achievable targets	Internal/external reuse of all general waste	3
	Innovative practices in reducing the general waste generation	2
	Subtotal	**5**

(continued)

Table 8 (continued)

Ecolabeling framework		
Clothing industry—from yarn storage to fabric manufacturing		
	Description	Points
Criterion 06	***Green House Gas (GHG)/carbon emission management***	***17***
Indicator 01	**Measures for the reduction of GHG emissions**	
Benchmark values and maximum/minimum achievable targets	Percentage GHG reduction from internal maximum GHG emission level (maximum allowable point is 9)	
	GHG reduction percentage > 50%	9
	20% ≤ GHG reduction percentage ≤ 50%	5
	Innovations and technological enhancements related to GHG emission reduction	3
	Conformance with ISO 14026: 2017 carbon footprint guidelines	5
	Subtotal	**17**
	Total points	**100**

Table 9 Final rating scheme

Points	Rating
40–49	Certified
50–59	Silver
60–69	Gold
70 and above	Platinum

5.6 Validation of the Framework

5.6.1 Assessment of the Degree of Consensus of the Experts on the Criteria and Indicators of the Ecolabel

Calculations of co-efficient variation of criteria based on the mean values and standard deviation values of percentage weights of criteria that were obtained from results of questionnaire analysis are shown in Table 10 whereas the graph of co-efficient of variation for criteria is shown in Table 10.

As shown in Table 10, co-efficient of variation of each criterion was between 0 and 0.5. According to the comparison with standard ranges of consensus, all criteria have achieved a good degree of consensus in the stakeholder analysis. Calculations of the co-efficient of variation of indicators based on the mean values and standard

Table 10 Co-efficient variation for criteria

Criterion	Standard deviation	Mean values	Co-efficient variation
Sustainable chemical management practices	3.42	18.28	0.19
Sustainable material usage	2.80	15.10	0.19
Energy conservation and management	2.90	16.15	0.18
Water, wastewater and effluent management	2.94	18.73	0.16
Solid waste management	3.18	14.97	0.21
Green House Gas (GHG)/carbon emission management	2.41	16.78	0.14

deviation values of percentage weights of indicators that were obtained from the results of questionnaire analysis are shown in Table 11.

Table 11 Co-efficient of variation for indicators

Indicator	Standard deviation	Mean values	Co-efficient variation
Minimizing restricted/hazardous chemicals	8.39	57.50	0.15
Best practices in chemical handling	8.39	42.50	0.20
Usage of organic materials	12.59	50.69	0.25
Usage of reusable/recyclable materials	12.59	49.31	0.26
Reducing overall energy intensity	9.86	49.60	0.20
Increasing renewable energy usage	9.86	50.40	0.20
Reducing overall water intensity	3.98	33.08	0.12
Enhancing water reuse	4.94	33.58	0.15
Industrial wastewater and effluent management	5.67	33.34	0.17
Management of industrial (non-hazardous) solid waste	5.77	32.59	0.18
Management of hazardous solid waste	4.68	35.70	0.13
Management of general waste	7.26	31.71	0.23

Table 12 Intraclass correlation coefficient for criteria

	Intraclass correlation	95% confidence interval	
		Lower bound	Upper bound
Average measures	0.900	0.737	0.983

Table 13 Intraclass correlation coefficient for indicators

	Intraclass correlation	95% confidence interval	
		Lower bound	Upper bound
Average measures	0.980	0.959	0.993

As shown in Table 11, co-efficient variation of each indicator was between 0 and 0.5. According to the comparison with standard ranges of consensus, all indicators have achieved a good degree of consensus in the stakeholder analysis.

5.6.2 Assessment of the Inter-rater Reliability

According to the ICC shown in Table 12, the average value for criteria was 0.900. This shows that there is a good reliability among criteria when comparing with standard ranges of ICC which were given in Table 5.

According to Table 13, the average ICC for indicators was estimated to be 0.980. This proves that there is an excellent reliability for indicators when comparing with standard ranges of ICC which were given in Table 5.

In general, there are two types of processes for yarn preparation as knitting and weaving. Knitting gives knitted fabrics while weaving gives weaved fabrics. Single thread can be used during knitting and in weaving two threads can be interlaced according to a design. Moreover, there are two major fabric types as printed fabric and dyed fabric. Generally, knitted surface is used for dying and printing. Dyed fabric consisted only one color while printed fabric consisted of different types of colors. Manufacturing processes have differed for each fabric, and therefore, energy, water intensity, and raw material usage can be varied. Generally, the consumption of water and energy for 1 kg of dyed fabric is larger than 1 kg of printed fabric. In addition, as the dying process requires one dye type while the printing process requires more dye types, and the raw material requirement is higher during printed fabric manufacturing. The ecolabeling framework which is developed can be applied for any of these different textiles which are developed within the Sri Lankan regional boundary.

6 Final Remarks

Life cycle of a garment is scattered from raw material acquisition to the disposal of the garment after its usage. When considering the clothing manufacturing process in Sri Lanka, more than 95% of raw materials (yarn) are imported whereas more than 40% of end products of the clothing industry is being exported. Therefore, the most applicable type of ecolabel to assess the life cycle stages operated within the regional boundary of Sri Lanka is a 'Gate-to-Gate' ecolabel.

However, as the extent within this scope is too broad, the scope between 'Yarn storage to knitted-dyed fabric manufacturing' was considered as the system boundary for the present work. The importance of the aforementioned system boundary is the considerable amount of environmental damage which is occurred within the gates of this system boundary due to high usage of chemicals, dyes, wastewater, solid waste, GHG emission, and considerable amount energy consumption through usage of high capacity machineries.

Out of those major criteria considered in global ecolabels, the most commonly used criterion was toxics for US, EU, and Asian ecolabels. Most of the EU ecolabels considered toxic as one of their major criteria since according to the European Textile Fibre Regulation, one of the main environmental objectives of countries such as Switzerland is maintaining a 'non-toxic environment'. Therefore, EU ecolabeling development agencies pay specific attention toward toxicity. Furthermore, there are significant health effects due to the toxicity of chemicals and dyes that are used in the clothing industry and there are many long-term negative effects to the environment due to the discharge of non-treated toxic effluent and wastewater. In addition, chemicals are the second most incorporated criterion as there is a significant relationship between toxicity and the chemicals.

In addition, as Benson and Reczek (2016) point out, several powerful agencies in the US such as the Environmental Protection Agency (EPA), Toxics in Packaging Clearinghouse (TPCH), and California Office of Environmental Health Hazard Assessment (OEHHA) are strongly linked with clothing industries through implementing mandatory regulations in order to achieve zero toxicity during the product life cycle chain. Therefore, more than half of the reviewed ecolabels have highly relied on toxicity as one of their major criteria.

As Asian countries follow International Labor Organization (ILO) regulations, the health and safety of employees is an integral part of all clothing industries. Therefore, they must pay high attention to toxicity that emerges especially with chemicals, dyes, fertilizer, and herbicides/fungicides/pesticides which also impose strong relationships with other criteria such as chemicals, herbicides/fungicides/pesticides, and wastewater. Hence, most of the ecolabeling frameworks have especially paid their attention toward toxicity.

Among the identified criteria and indicators through the extensive literature review, potential criteria for the Sri Lankan clothing industry were identified as sustainable chemical management practices, usage of sustainable materials, energy conservation and management, water and wastewater management, solid waste management, Green House Gas (GHG)/Carbon emission management. Indicators were also identified under each and every criterion. Then the relative weights for each criterion and indicator were finalized through a questionnaire survey.

According to the weights given by the respondents of questionnaire survey, highest importance was given to water and wastewater management followed by chemicals, GHG/Carbon emission management, energy conservation and management, usage of sustainable materials, and solid waste management. Therefore, during the development of ecolabeling framework, the highest point was allocated for water and wastewater management followed by chemicals, GHG/Carbon emission management, energy conservation and management, usage of sustainable materials, and solid waste management. Total sum of points was 100.

As per the outcomes from the questionnaire survey, water and wastewater management has the highest importance within the considered system boundary of this research as a large amount of water is required for the process of dyeing and a significant amount of wastewater and effluent are discharged from clothing industries. There, untreated toxic wastewater and effluent may be released into the water sources.

According to the majority of the respondents, water and wastewater management should be thoroughly concerned as it may lead to creating huge negative environmental impacts. Furthermore, according to the results of the questionnaire survey, solid waste management had the least importance. The reason behind this could be the clothing industries paying less attention toward solid waste management as less amount of hazardous solid wastes are generated during the selected system boundary while most of the non-hazardous solid waste are reused or recycled. Therefore, less damage is occurred to the environment through the solid waste.

As stated before, there are four ecolabels that are used by Sri Lankan clothing industry. They are Fairtrade, GOTS, IMO Certified, and Naturland e.V. As stated in Fair Trade USA (2017), in the Fairtrade ecolabeling framework, there is a section called Environmental Responsibility and Management (ERM) and there are three subsections called Monitoring Systems (MS), Hazardous Materials (HM), and Waste Management (WM). Monitoring of environmental policies, legal permits, and Environmental Management System (EMS) are carried out under ERM. Storage, usage, disposal of chemicals, and toxic and hazardous substances elimination are mainly concerned through HM while WM is considered about disposal of chemical waste, solid waste, and liquid waste.

In the present work, environmental policies, laws, and regulations were not taken into account as they are already monitored by Central Environmental Authority (CEA) Sri Lanka. Moreover, indicators and benchmark values and maximum/minimum target values of HM in Fairtrade are almost the same as the criteria of sustainable chemical management practices in this research. However, wastewater and solid waste are combined as one subsection of WM in Fairtrade. In the proposed framework, there are two separate criteria for wastewater and solid waste as water and wastewater management and solid waste management. However, majority of the respondents of the questionnaire survey indicate that wastewater has the highest importance while there is less importance for solid waste. Hence, a combination of these two criteria together is not reasonable for Sri Lankan scenario similar to Fairtrade ecolabel.

GOTS is another ecolabel that is used in Sri Lankan clothing industry. It considers about chemicals, Genetically Modified Organisms (GMOs), material use, natural resources, pesticides/herbicides/fungicides, soil, toxics, wastewater/sewage, and water quality as its main criteria. Some specific criteria for clothing industry such as energy consumption and GHG emission which could have a high priority when it comes to the selected system boundary that is operated within Sri Lanka. The reason for the importance of these criteria for Sri Lankan scenario is that a considerable amount of machineries are used with the gate-to-gate system boundary of this research. Therefore, energy consumption and GHG emission of different machinery during different processes shall be highly concerned through an ecolabeling framework that is applicable to Sri Lanka. Furthermore, GOTS has a major focus on maintaining the organic status of garments.

Similarly, IMO Certified ecolabel's major focus is on chemicals, forests, pesticides/herbicides/fungicides, soil, and toxics as within the scope of cradle to grave. However, energy efficiency, water and wastewater, solid waste, and GHG emission are highly important to Sri Lankan clothing industry more than some criteria used in IMO certification such as pesticides/herbicides/fungicides and soil. The reason behind this is most of the criteria in IMO Certified products like forests, pesticides/herbicides/fungicides, soil are particularly related to the raw material acquisition. However, in Sri Lankan scenario, a high usage of machineries within the gate-to-gate scope, an ecolabel that pays specific attention about energy efficiency, wastewater, and GHG emission could be an integral component for an ecolabel in Sri Lankan clothing industry.

In addition, Naturland e.V. which is highly focused on raw material acquisition (especially farming) has highlighted the values of nine criteria as animal welfare, biodiversity, chemicals, forests, GMOs, natural resources, pesticides/herbicides/fungicides, soil, and toxics. As stated above, in Naturland e.V., less important criteria to Sri Lankan clothing industry such as animal welfare, pesticides/herbicides/fungicides, and GMOs are given a high priority whereas highly important criteria to Sri Lankan clothing industry such as energy efficiency, water and wastewater are slightly concerned.

Usage of certified raw materials implies that the scopes before yarn storage to fabric manufacturing are environmentally friendly and have achieved its sustainability with the early stages of its life cycle that are not covered within the gates of the proposed ecolabel. Unless these scopes are eco-friendly, life cycle of a cloth cannot be completely eco-friendly. Appointment of one or more qualified personal responsible to industry's compliance on the applicable ecolabel criteria system should be further administrated for the proper management of the processes within the boundary of Sri Lankan clothing industry in order to achieve the ecolabeling criteria and indicators.

References

1. Central Bank (2016) Annual report 2016. https://www.cbsl.gov.lk/en/publications/economic-and-financial-reports/annual-reports/annual-report-2016. Accessed 28 Feb 2022
2. Chen HL, Burns LD (2006) Environmental analysis of textile products. Cloth Text Res J 24(3):248–261
3. Dheerasinghe R (2009) Garment industry in Sri Lanka challenges, prospects and strategies. Staff Stud 33(1)
4. Ecolabel Index (2022) All ecolabels on textiles. http://www.ecolabelindex.com/ecolabels/?st=category,textiles. Accessed 15 May 2022
5. English JM, Kernan GL (1976) The prediction of air travel and aircraft technology to the year 2000 using the Delphi method. Transp Res 10:1–8
6. Gam J, Cao H, Farr C, Kang M (2010) Quest for the eco-apparel market: a study of mothers' willingness to purchase organic cotton clothing for their children. Int J Consum Stud 1–9
7. Gamage TC, Abeysinghe D (2010) Strategy for achieving ecological sustainability while improving business performance: a field study in textile & clothing industry
8. Gereffi G (2002) Outsourcing and changing patterns of international competition in the apparel commodity chain. Paper presented at the conference on responding to globalization: societies, groups, and individuals, Hotel Boulderado, Boulder, Colorado, April 4–7. http://www.colorado.edu/IBS/PEC/gadconf/papers/gereffi.pdf. Accessed 16 Mar 2022
9. Green Council (2017) Hong Kong Green Labelling Scheme (HKGLS), Hong Kong. http://www.greenlabel.com.hk. Accessed 15 Aug 2021
10. Hokkanen J, Salminen P, Rossi E, Ettala M (1995) The choice of a solid waste management system using the ELECTRE II decision-aid method. Waste Manage Res 13:175–193
11. Jha A (2018) Apparel industry in Sri Lanka: expected growth in 2018. https://www.bizvibe.com/blog/apparel-industry-in-sri-lanka/. Accessed 15 Sept 2021
12. Keller G, Warrack B (2003) Statistics for management and economics. Thomson, USA
13. Kodikara PN (2008) Multi-objective optimal operation of urban water supply systems. Victoria University
14. Koo TK, Li MY (2016) A guideline of selecting and reporting intraclass correlation coefficients for reliability research. J Chiropr Med 15(2):155–163
15. Nayak R, Padhye R (2015) Introduction: the apparel industry. In: Garment manufacturing technology, pp 1–17
16. SLAEA (2015) Sri Lanka garments committed to sustainable manufacturing 2015. Journal and directory of the Sri Lanka apparel exporters association (89)
17. SLAEA (2017) Sri Lanka garments committed to sustainable manufacturing. Journal and directory of the Sri Lanka apparel exporters association (90)
18. Saranaweera HK (2017) Development of an eco labelling system for cement in Sri Lanka. BSC thesis, University of Ruhuna, Mapalana, Kamburupitiya
19. Senaweera LN, Parasnis S (2018) Recommendations for eco-labelling platform for Sri Lanka. SWITCH-Asia SCP NPSC SL Projectm, viewed 2 March 2021. scp.mmde.gov.lk/kdb/.../Report%20Eco%20Labeling%20Platform%2020180511.pdf. Accessed 2 June 2022
20. Sinha P, Shah R (2010) Creating a global vision for sustainable textiles
21. Sparshott J (2005) Nations request trade relief. The Washington Times
22. Statista (2019) Market demand of clothing in Taiwan from 2011 to 2018 (in billion U.S. dollars). https://www.statista.com/statistics/616629/taiwan-clothing-market-demand/. Accessed 2 Jan 2022
23. Statista (2019) Retail volume of the apparel industry in Japan from 2011 to 2020 (in billion units). https://www.statista.com/statistics/665190/japan-fashion-industry-retail-volume/. Accessed 2 Jan 2022
24. UNOPS (2009) A guide to environmental labels—for procurement practitioners of the United
25. West K (1995) Ecolabels. The industrialization of environmental standards. Ecologist 25(1):16–20
26. Yuasa M (2001) Globalization and flexibility in the textile/apparel industry of Japan. Asia Pac Bus Rev 8(1):80–101

Recent Progress on Life Cycle Sustainability Assessment in Textile Industry: Applications for Environmental, Economic, and Social Impacts of Cotton and Its Derivatives

Fatma Şener Fidan, Emel Kızılkaya Aydoğan, and Nigmet Uzal

Abstract As a result of the fast fashion trend, consumer shopping habits have altered, and clothes sales have surged at an unforeseen rate. It is anticipated that this tendency would continue, with a 63% increase by 2030. The textile business focused on long-term solutions despite the fact that rising consumption produces environmental, economic, and social concerns. In addition, customers began to be concerned with the environmental, economic, and social implications of textile products. Cotton has been used to manufacture textiles since prehistoric times and is currently the most popular natural material for textiles. Therefore, it should be closely monitored throughout the period. As an alternative to conventional cotton, environmentally and socially sustainable cotton cultivation variants such as organic and responsibly sourced certified cotton have evolved, and their use is rising rapidly. Furthermore, as the circular economy model gains popularity, academics and business have concentrated on mechanical and chemical recycling solutions to give cotton fiber a second life. Numerous research on the life cycle assessment of these cotton textiles and apparel have been published. According to these studies, cotton production has significant environmental implications because of its high water consumption, land occupation, energy, fertilizer, and pesticide use, all of which can impact the environment and human health. The cotton industry has the greatest impact on water consumption and drought, accounting for 2.6% of global water consumption. Acidification and eutrophication have detrimental environmental effects; pesticide use accounts for 11% of global consumption and roughly 50% of consumption in developing nations. In addition, when energy-intensive inputs such as fertilizers, herbicides, seeds, diesel fuel, and electricity are used, cotton growing is a large contributor to greenhouse gas

F. Ş. Fidan (✉)
Department of Technology Transfer Office, Abdullah Gul University, Kayseri 38170, Turkey
e-mail: fatmasener@gmail.com; fatma.senerfidan@agu.edu.tr

E. K. Aydoğan
Department of Industrial Engineering, Erciyes University, Kayseri 38060, Turkey

N. Uzal
Department of Civil Engineering, Abdullah Gul University, Kayseri 38170, Turkey

S. S. Muthu (ed.), *Progress on Life Cycle Assessment in Textiles and Clothing*,
Textile Science and Clothing Technology,
https://doi.org/10.1007/978-981-19-9634-4_7

emissions, accounting for between 0.3 and 1.0% of the total global warming potential. Due to the fact that it is cultivated on around 2.3% of the world's agricultural land, it has significant land use potential. In addition, research conducted in the textile industry reveals that it frequently entails a variety of concerns for stakeholders such as employees, local communities, players in the value chain, and society. Despite the infancy of social life cycle assessment research for textile products, the number of studies on this topic is gradually increasing. This chapter examines previous research to gain an understanding of current practices, advancements, and challenges in the use of life cycle assessment in the environmental, economic, and social dimensions of cotton raw material in the textile industry. Existing life cycle assessment studies were extensively described and grouped using content analysis according to the researched sustainability dimension and cotton type. Finally, the current uses, advancements, and challenges of life cycle assessment in cotton raw material for the textile industry, as well as future recommendations, were addressed. It is hoped that the study's findings will encourage others to perform additional research in the field of environmental, economic, and social life cycle assessment.

Keywords Cotton · LSCA · LCA · Environmental impacts · Economic impacts · Social impacts

1 Introduction

The textile industry is currently one of the most crucial sectors of the global economy [1]. The global market for textiles is expected to rise at a compound annual growth rate of 4% between 2022 and 2030, reaching a value of 993.6 billion US dollars in 2021 [2]. Daily clothing demand is increasing due to the quick fashion trend in the textile business [3]. Employment has increased, the textile and agricultural industries have expanded, and these developments have all contributed to the generation of substantial quantities of foreign currency as a result of the expansion of e-commerce-driven demand [4].

This rise illuminated the sector's environmental and social problems. This industry, which has major environmental implications because of its high consumption of raw materials, chemicals, and water, is the second largest contributor to global carbon emissions [5, 6]. Moreover, as a labor-intensive business, the textile industry has many social implications as well as environmental ones. Numerous social issues, ranging from working conditions to health risks, are crucial for the textile sector, whose intricate supply chain involves multiple countries and raw materials. As production shifts to countries with inexpensive labor, social issues such as low salaries, gender discrimination, child labor, excessive working hours, and temporary employment contracts have become significant [7]. Some non-governmental organizations (NGOs) that elevate social issues to the agenda in order to enhance the working conditions of their employees and community development have initiated long-term campaigns to draw attention to these issues [8]. In response to these demands, major brands like Nike and H&M have incorporated socially responsible practices into their supply chains [9, 10].

In life cycle assessment (LCA) research concerning the environmental dimension in the textile industry, which has made significant strides in disclosing environmental effects, it has reached saturation. Additionally, it has been extensively explored in the literature. Cotton farming [11–13] fiber manufacturing, and fabric manufacture [5, 6, 14, 15] and garments such as T-shirts, jeans, etc., [16–18] have benefited from this research. While environmental life cycle assessment has made great strides, social life cycle assessment (S-LCA), a key tool for assessing the social ramifications of a product or process, has lagged behind. The lack of agreed-upon indicators and methods, such as in environmental LCA app lications, is the fundamental cause of this sluggish rate of growth [19, 20]. The S-LCA guidelines and methodological papers issued by UNEP/Society of Environmental Toxicology and Chemistry (SETAC) gave it a boost, although these obstacles remain [21–23]. With the publication of "Guidelines 2020 for the S-LCA of products, and organizations" the technique continues to evolve [23].

The Sustainable Development Goals (SDGs) of the United Nations are a worldwide call to action to eradicate poverty, protect the planet, and guarantee that all people can live in peace and prosperity [24]. It seeks to improve environmental, economic, and social conditions. For this reason, the use of the life cycle costing (LCC) method, which incorporates life cycle thinking, should also be incorporated into the economic evaluation. However, this textile industry research is still in its infancy.

This chapter analyzed prior research to comprehend the present practices, innovations, and problems of life cycle thinking in the environmental, economic, and social components of the textile industry's cotton fiber supply chain. Existing studies have been meticulously defined and classified using content analysis based on the researched sustainability factor and the type of cotton employed. Finally, the current applications, advancements, and challenges of LCA, S-LCA, and LCC methodologies in the cotton supply chain for the textile industry were examined, along with future recommendations. The findings help to increase the sustainability of the cotton supply chain, and the number of studies conducted in environmental, economic, and social dimensions while shedding light on the complexities of the approaches and making significant contributions to their growth. In the second section of this chapter, an overview of the textile industry and its primary raw materials is presented. In addition, this part contains information regarding the usage rates and varieties of cotton raw materials. Section three covers general information regarding sustainable development and sustainability assessment approaches. The fourth section defines life cycle sustainability assessment (LCSA) and the LCA, LCC, and S-LCA methods used in the evaluation of the three dimensions of sustainability, as well as the processes of these methods. In the fifth section, environmental studies including the evaluation of cotton textiles with LCA have been evaluated through a literature analysis. In the sixth and seventh sections, studies examining the economic and social aspects of cotton textiles are evaluated, respectively. The chapter concludes with a discussion of the Present, and Future of Life Cycle Sustainability Assessment in the Textile Industry.

2 Textile Industry and Cotton as a Raw Material: An Overview

As one of the oldest sectors, the textile industry contributes significantly to national economies. The size of the global textile market in 2021 is projected to increase at a CAGR of 4.0% between 2021 and 2030 [25]. From 2022 to 2030, it will grow at a stable CAGR because of rising environmental concerns and a shift toward sustainable products, which will enhance consumer demand for natural fiber. The sector begins with the design of products such as apparel and home textiles, continues with the manufacture of yarn and fabric, the garment phase, retailing, the use phase, and concludes with the end-of-life phase. Fiber is the primary raw material of the textile industry. The world's fiber output is projected to reach 109 million tons in 2020, up from 58 million tons in 2000. Textile Exchange's Preferred Fiber & Materials Market Report 2021 provides the data shown in Fig. 1 regarding the prevalence of various fiber types in the industry [26].

In 2021, according to the data, synthetic fibers held 62% of the market share. Polyester was the most popular form of synthetic fabric at 52%. Cotton was the most popular natural fiber, accounting for 24.2% of plant fibers, which accounted for a 30% share. Cotton, one of the oldest fibers in history, possesses several significant

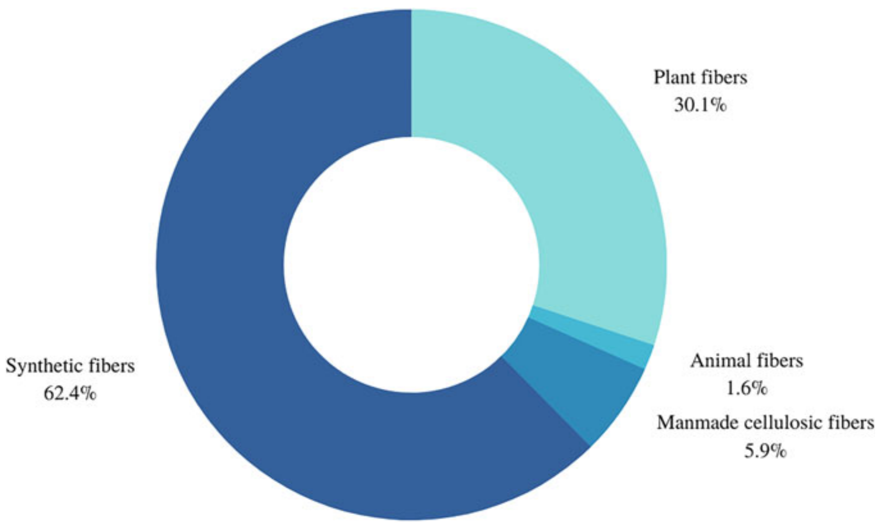


Fig. 1 Distribution of global fiber varieties (retrieved Preferred Fiber & Materials Market Report 2021) [26]

properties for the textile industry, including great strength, absorbency, and color retention.

In the 2022/23 marketing year, global cotton production was estimated at 1,2065 tons. The phrase crop/marketing year is typically applied to crops and represents planting and harvesting cycles. The harvest year for cotton is from August 1 to July 31. The World Cotton Supply is depicted in Fig. 2.

It is anticipated that cotton production has increased by 1.5% annually over the past two decades. This rise is anticipated to be driven by expansion of the cotton field (0.5% per year) and average global yield growth (1% per year) [28]. The yield ratio has stayed steady despite the fact that numerous nations are battling pest infestations and water constraint, and the output share of low-yielding nations has increased. The adoption of improved genetics and agronomic techniques for sustainable cotton production is anticipated to increase during the next decade. China, India, the United States, and Brazil are, successively, the world's biggest producers of cotton. Figure 3 depicts the production amounts of the top cotton-producing nations for the 2021/22 marketing year.

Although cotton is an extensively utilized and renewable natural seed fiber, it poses numerous environmental and social issues. Human health and the environment are negatively impacted by conventional cotton agriculture, which is characterized by interconnected environmental, social, and economic issues. Table 1 provides a

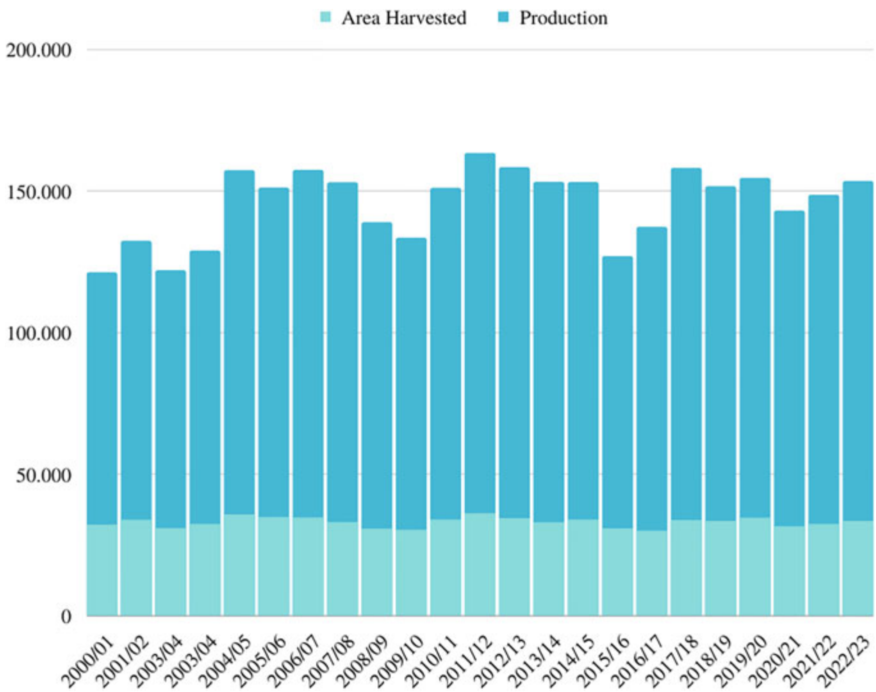


Fig. 2 World cotton supply (1,000 HA and 1000 480-lb. Bales) [27]

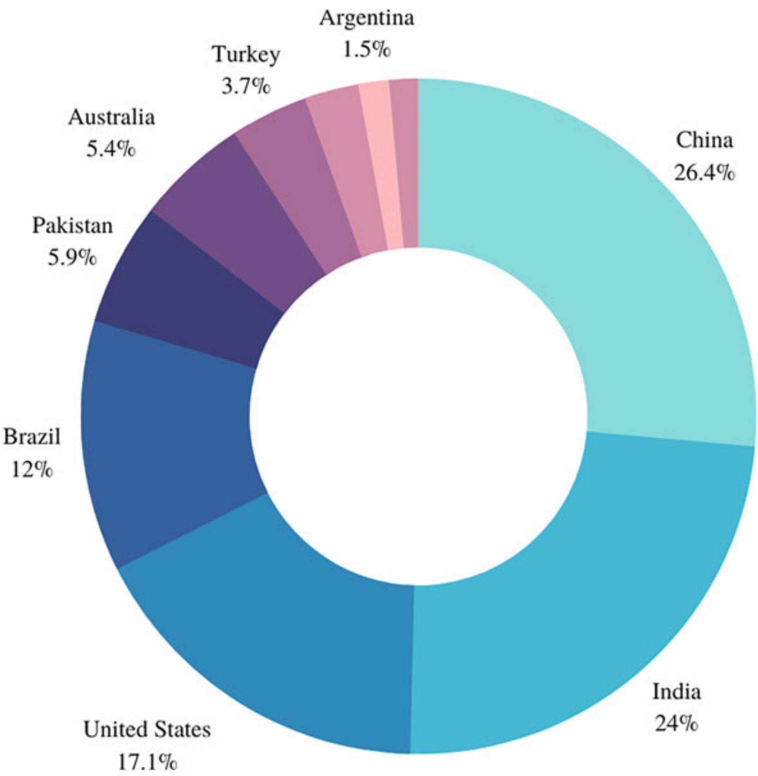


Fig. 3 Cotton supply's distribution by country 2021/22 (Thousand metric tons) [29]

summary of the research findings about cotton production environmental impacts. It should be noted that these results vary depending on the study's location and time of year.

In addition to these environmental consequences, it is crucial to assess the social effects of the cotton supply chain. As 1.1 billion people are employed in agriculture, the sector has a direct relationship with humans [39]. In addition, small breeders use a considerable number of temporary and family workers. Unpaid family members labor in agriculture to support unregistered family farms. Agriculture, which is often favored by the poor in rural areas, is fraught with numerous social issues. For instance, the Rana Plaza collapse in 2013 and the deaths of 1,129 people demonstrate the severity of the industry's challenges [40]. Table 2 provides a summary of the issues raised in the literature about cotton production.

Changing cotton production in response to the aforementioned environmental concerns is currently the sector's top priority. Non-profit Textile Exchange (TE) is the most significant institution in this industry. TE, which is comprised of prominent brands, retailers, and suppliers, conducts research to favorably impact the climate by advancing the global textile industry's usage of preferred fibers. The most significant

Table 1 Environmental concerns regarding cotton production

Environmental concern	Impact area	References
Cotton production causes drought by consuming 2.6% of the world's water	Water consumption	[30]
Due to their propensity for acidification and eutrophication, the amount of pesticides used in cotton cultivation, which is 11% of global consumption and around 50% in developing nations, has adverse environmental effects	Toxic, and polluting chemical	[31]
Cotton farming utilizes 2.5% of the world's arable land yet employs 16% of all insecticides	Toxic, and polluting chemical	[32]
In India, cotton farming uses 50% of all insecticides	Toxic, and polluting chemical	[33]
Cotton farming contributes between 0.3% and 1% to the global warming potential due to the use of fuels or fertilizers, pesticides, seeds, irrigation energy, and machinery fuel	Energy consumption	[33]
Since cotton is grown on around 2.3% of the globe's farmable land, it has a significant land utilization potential	Soil pollution	[34]
Per kilogram of cotton around 412 L of irrigation water are required	Water consumption	[35]
25% of the global insecticides consumed are employed in cotton production	Toxic, and polluting chemical	[36]
Globally, 53% of cotton fields are irrigated, which translates to 73% of cotton production because irrigated cotton often offers greater yields per unit area	Water consumption	[37]
An estimated 12% to 36% of cotton-growing land in the twelve top cotton-producing nations is affected by salinization. When evapotranspiration surpasses precipitation, soil salinization occurs and poses a concern, especially in irrigated areas	Toxic, and polluting chemical	[31]
The average electricity consumption per bale ranged from 46.55 to 58.55 kWh	Energy consumption	[38]

(continued)

of these initiatives is the 2025 Sustainable Cotton Challenge, which he launched in 2017 in the cotton industry. When firms and retailers commit to purchasing 100% of the cotton using sustainable sources by 2025, it will act as a catalyst for transformation in the apparel and textile sectors and benefit the environment. The 2025 Challenge seeks to promote the use of preferred cotton in order to boost the income of small-scale farmers, minimize the use of very dangerous pesticides, and lessen the need for water and fertilizers while simultaneously bettering soil quality and water quality.

Table 1 (continued)

Environmental concern	Impact area	References
It is estimated that 3,644 cubic meters of water are required to produce one ton of seed cotton, which is almost the same as the volume of 1.5 Olympic-sized swimming pools	Water consumption	[33]
Ten of the most toxic insecticides are regularly used to cultivate cotton	Toxic, and polluting chemical	[33]
Cotton is one of the world's top three genetically modified crops. According to the Indian government, more than 70% of India's cotton production area is currently comprised of cotton with genetically modified organisms (GMOs)	Toxic, and polluting chemical	[33]
GMOs usage causes biodiversity loss	Toxic, and polluting chemical	[33]

TE uses the term "preferred cotton" (pCotton) to refer to cotton that is supplied more responsibly than conventionally produced cotton. The classification of "preferred" is determined by the following criteria: possibility for circularity; the capacity to track fibers across the supply chain; adherence to defined sustainability requirements; confirmed sustainable qualities; and conformity to a recognized industry standard [42]. Listed below are the most important initiatives included in the categorization as proposed by TE:

- ABRAPA
- BASF e3
- Better Cotton Initiative (BCI)
- Cotton made in Africa (CmiA)
- Fair Trade Organic
- Organic cotton
- Recycled Cotton
- Transition Cotton
- United States Cotton Trust Protocol

In 2012/13, pCotton was used at a rate of 5%, but by 2019/2020, it had attained a 30% share. Figure 4 depicts the trend of the pCotton fiber consumption rate, as reported by TE 2021 [43].

Figure 5 depicts the distribution of pCotton's activities for the 2019/20 marketing year. pCotton holds a 30% market share and has a variety of initiatives within itself. Examining the allocation of pCotton initiatives revealed that 41% of the weight belongs to BCI Standard and 37% to ABRAPA. BCI certifies cotton based on the Better Cotton Standard System, which encompasses all three pillars of sustainable cotton production (environmental, social, and economic). As it provides an easier entrance point than organic, its popularity is considerable. The ABRAPA promotes the development of strong social, environmental, and economic principles for the sustainable management of farms. To be accredited, each production unit must adhere

Table 2 Social concerns regarding cotton production

Social impact	Dimension	References
270,000 + Indian cotton growers have taken their own lives since 1995. Opponents of GMOs argue that the market saturation of expensive GMO seeds is to blame, placing pressure on low-paid growers and driving many into an uncontrollable spiral of debt. Each year, farmers are required to purchase fresh GMO seeds by patent restrictions; seeds from previous years cannot be used	Worker	[41]
Cotton is cultivated in more than 80 countries, and cotton production supports around 350 million people. When the market is robust, it benefits employees, but when it declines or a crop fails, it can bring great suffering for them. Economically, farmer incomes are exposed to the volatility of global markets. Existing low incomes are constantly threatened and may decline further. During the 2001/02 season, when global cotton prices fell by 40%, rural poverty in Benin's cotton-growing regions grew by 8%	Worker	[41]
In a number of the world's leading cotton-producing nations, poor working conditions and incidents of child and forced labor pose significant social difficulties. As of September 2016, the United States According to the data provided by the United States Department of Labor, cotton-growing enterprises in eight of the top 10 cotton-producing countries make use of either child labor or forced labor. These producer nations account for more than 80% of the yearly global cultivation	Worker	[41]
Global trade structures are frequently detrimental to farmers. In addition, the high price of inputs like GMO seeds, herbicides, and fertilizers has left many farmers in the loan	Worker, Value chain Actors	[41]
Lack of gender equality, a major concern in the agricultural industry, impedes inclusive growth in cotton-growing communities	Worker	[41]

to 178 conditions, including spring protection, soil and biome preservation, and worker health, safety, and well-being. Utilizing organic cotton is an additional significant trend in the industry. There are numerous certification schemes for organic cotton around the globe, such as the Global Organic Textile Standard (GOTS) and Organic Content Standard (OCS). However, the proportion of organic cotton in pCotton was restricted to 3%.

Moreover, regenerated cotton is the most sustainable sort of cotton. Made-By, a program that evaluates the sustainability of textile fibers, has given it the highest possible grade of A. Recycled cotton produced from post or pre-consumer waste is

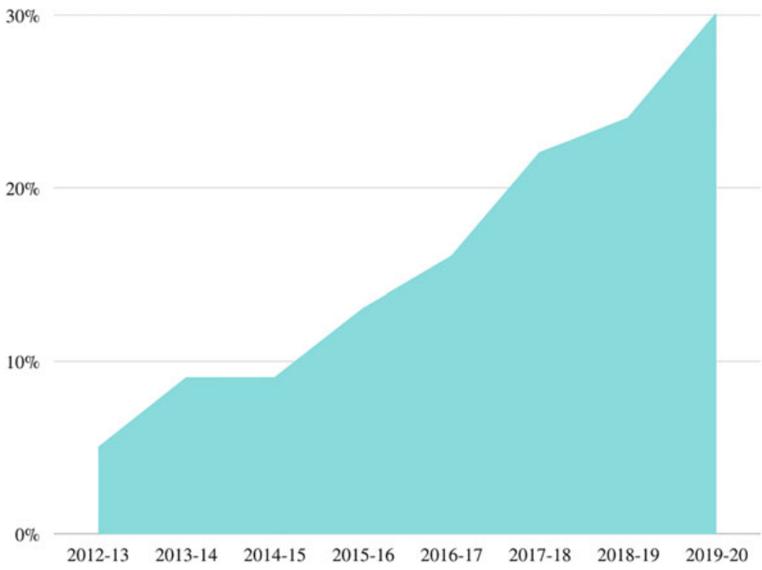


Fig. 4 Trend of pCotton fiber production ratio [43]

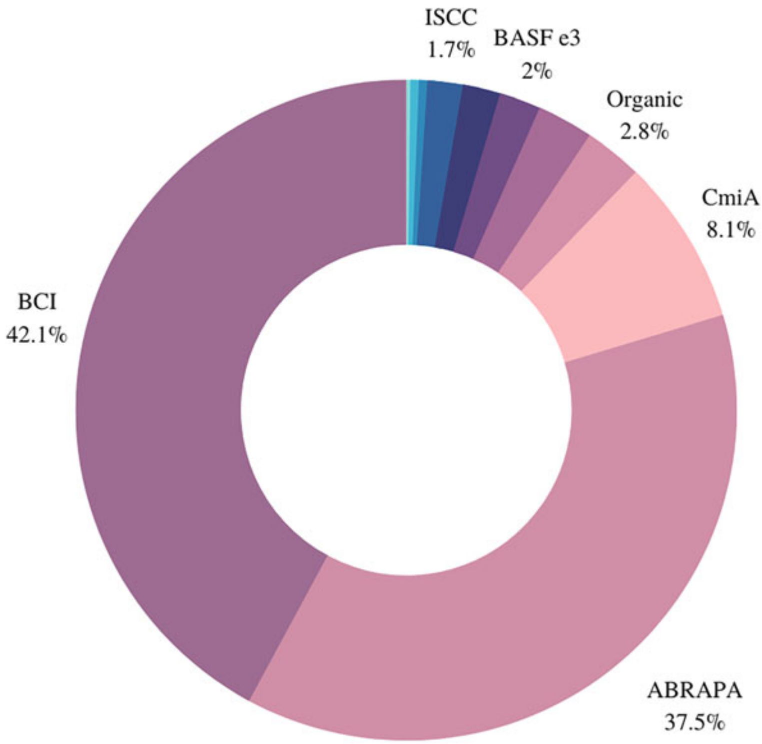


Fig. 5 Cotton initiatives ratio included in pCotton [43]

offered in a variety of standards. The Recycled Demand Standard (RCS) and Global Recycling Standard (GRS) offer certification requirements for items containing a specified percentage of recycled cotton. While recycled cotton is vital to the sustainability of the cotton supply chain, its proportion of the global cotton fiber market will remain small in 2019/20 at 0.96% or 0.26 million tons.

Consequently, cotton has maintained its position and significance in the textile industry since antiquity. However, traditional cotton farming and production practices contribute negatively to global climate change by creating numerous adverse environmental effects, such as soil degradation, intensive use, and water pollution. Due to this, the sector has already begun considerable transition and reached an advanced stage. The use of cotton and cotton that has been recycled is expanding daily, and numerous organizations promote these activities.

3 Progress of Sustainability Development

The capacity of the global resource system to deliver resources for the ever-growing human population is limited [44]. The industrial revolution has led to a rise in production. The world's resources are insufficient to sustain the current rate of production and consumption growth. When economic development was sought in the early twentieth century, it was considered that air and water were free and infinite. With a growing global population, diminishing natural resources, and concerns such as global warming, it has become evident that the existing economic outlook cannot be maintained. Figure 6 depicts the evolution of sustainability development throughout history.

First recognized in 1972 at the United Nations Conference on the Human Environment, industrialization's effects on the natural world were analyzed in detail. Additionally, it was the site where the United Nations Environment Program was founded (UNEP). The Limits to Growth study was also published at the meeting [46]. This paper used computer modeling to demonstrate that the world's current resources cannot support the exponential population and economic development. The conference is widely recognized as the pioneering global forum dedicated to the study of sustainability. In the conference's declaration, 26 principles were agreed upon, including social, environmental, and economic components, as well as action recommendations [47]. This was the first meeting on the environment organized by the United Nations.

Our Common Future Report that included the first official institutional description of sustainable development was released by the World Commission on Environment and Development in 1987 [48]. According to the definition provided in the paper, sustainable development is an achievement that guarantees the requirements of the present generation are addressed without sacrificing the needs of succeeding generations. It has been underlined that a purely economic viewpoint is insufficient to address human needs, and that social and environmental concerns must also be given adequate consideration. Thus, the narrow perspective, which only included

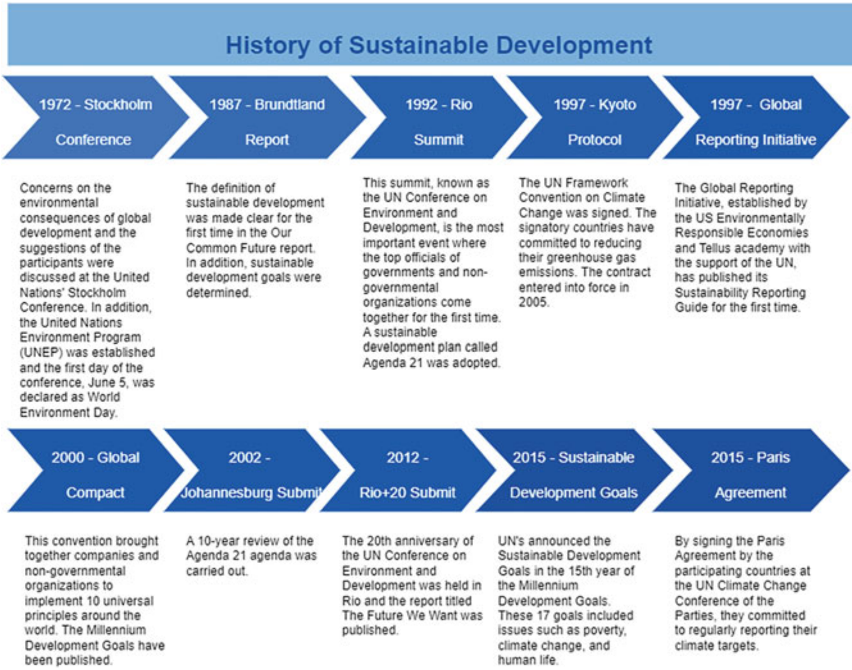


Fig. 6 History of sustainability development [45]

the environmental aspect, has been broadened, and social issues have begun to be included. Consequently, the concept of sustainability has developed. According to [49], this notion encompasses natural, social, human-created, social, cultural, and scientific phenomena, among others. It was a participative process that establishes and upholds a societal perspective on securing and respecting the sensible use of resources [49].

The first roadmap to sustainability was formed during United Nations Conference on Environment, and Development [50]. This action plan, known as Agenda 21, was founded on voluntarism, much like the principles of corporate governance. Although the action plan addressed issues pertaining to the social dimension, such as the eradication of poverty, the majority of its concerns pertained to the environmental dimension. The Kyoto Protocol, the Rio Declaration, Agenda 21, the Framework Convention on Biological Diversity, the Framework Convention on Climate Change, and the Framework Convention on Deforestation were significant outcomes of this meeting.

The signing of the Kyoto Protocol in 1997 was a significant milestone of the 1990s. This protocol, which is part of the UN Framework Convention on Climate Change, is the first global agreement to address climate change. Three concepts, the preventive principle, shared but differentiated responsibility, and the right to development, were adopted by the convention [51]. As a result, the emissions of the

40 most industrialized countries should be lowered by at least 5% from 1990 levels between 2008 and 2012.

In the year 2000, 189 heads of state attended the Millennium Summit held in New York [52]. The Millennium Declaration, which was published at the summit, outlined eight goals to enhance and develop strong global partnerships. Goals included ending world hunger, completing primary education for all children, closing the gender gap, decreasing maternal and infant mortality, preventing the transmission of HIV/AIDS, tuberculosis, and malaria, stopping the depletion of the earth's resources and biodiversity, and guaranteeing everyone a safe place to live with access to clean water and decent housing. This meeting symbolized an unprecedented global consensus on reducing poverty [53].

World Sustainable Development Conference (Rio + 10), placed in Johannesburg in 2002, South Africa, and the delegates reaffirmed their commitment to achieving sustainable development [54]. What has been accomplished in the ten years since the Rio Earth Summit was analyzed and the Political Declaration and Implementation Plan were drafted, which reflect the political will? In contrast, in the Implementation Plan, targets were established for renewable energy, chemicals, natural resources, and climate in general.

In 2012, twenty years after the World Sustainable Development Summit, world leaders convened at the "Rio + 20" summit and agreed on important concepts [55]. Social, economic, and environmental priorities have not been addressed concurrently, resulting in unequal progress, and eradicating poverty has been identified as the world's greatest problem. At the conference, the report titled The Future We Want was published.

In 2015, New York City hosted the United Nations Sustainable Development Summit which is a significant milestone in this sector. It has defined 17 sustainable development goal areas in addition to the Millennium Development Goals [56]. The primary objective of the summit was to free humanity from the tyranny of poverty and to safeguard and heal our planet. With these goals, which define and outline the scope of sustainable development, it is now evident to everyone what must be accomplished. The Paris Agreement on climate change reduction, resilience, and finance was signed in 2015 in compliance with the United Nations Framework Convention on Climate Change [57].

This concept is difficult to evaluate because of its expansive breadth and ever-changing objectives, as evidenced by a review of important milestones from the emergence of sustainable development to the present. In order to attain sustainable development objectives, further research is being conducted on a variety of assessment methodologies, with LCA being the most prevalent technique being employed. Details regarding the LCA are provided in the following section.

4 Sustainability Assessment Methods with Life Cycle Thinking

4.1 Life Cycle Sustainability Assessment

There are three components of sustainability, each of which is analyzed separately before being brought together. The LCSA is an integrated strategy based on the triple bottom line and life cycle thinking [58]. According to [59] formulation, LCSA = LCA + LCC + S-LCA [59]. LCA refers to environmental assessment with the ISO 14040 and 14,044 Standards, LCC to the economic dimension, and S-LCA to the social dimension. All of these methods have their own methods, evaluation scales, and challenges, thus they must be analyzed independently.

4.1.1 LCA

The LCA method is an analytical technique for analyzing the effects that a product has on the surrounding environment over its entire life cycle, from manufacturing to disposal, identifying problem areas, and drawing conclusions from those analyses. The methodology included calculations for all processes, beginning with the procurement of raw materials and continuing through production, transportation, use phase, and end of life. The process for implementation has been standardized with ISO 14040, and 14,044 Standards [60, 61]. This standardized procedure includes four steps.

- **Goal and scope definition**: It is anticipated that the objective of the work to be performed will be specified prior to its commencement. LCA can be performed for goals like comparing products, detecting hot spots, and identifying chances for improvement. It is conducted in the textile industry, particularly by companies that manufacture intermediate items such as fabric and yarn, to determine the effects of their products. In addition, the determination of the functional unit is a crucial factor. A product system's functional unit is its measurable performance that may be used as a standard. For instance, choosing a unit such as 1 m of fabric in an LCA analysis to be conducted for fabric is insufficient. This unit is unsuitable because the width and weight of one meter of fabric varies depending on the fibers it contains. Since the functional unit should be unambiguous, it is more precise to specify one meter of fabric in kilograms or square meters. At this step, the scopes to be applied to the LCA research should be determined. Methods including cradle to gate, cradle to grave, cradle to cradle, and gate to gate are available. This selection is determined by the goal of the study and several criteria, such as the availability of data.
- **Inventory analysis**: It entails gathering information on the inputs and outputs that will be used to execute the LCA work for the scope and restrictions established at this stage. It can be described as the most crucial and difficult step of the LCA

study. This step, which begins with the drawing of the process diagram within the scope specified in the previous step, involves the determination of inputs such as raw materials, energy, and water for the functional unit, as well as outputs such as product, waste, and emissions. LCA is a data-intensive process, and the findings obtained are totally dependent on the data's quality and dependability. In circumstances where no data are available, published literature, reports, and databases from various institutions are reviewed. The creation of databases such as Ecoinvent and Gabi in this field is one of the primary causes for the rise in LCA research over the past few decades [62, 63]. It is now easier to conduct cradle-to-grave LCA assessments as a result of these databases holding extensive data. Frequent usage of sensitivity and uncertainty analysis to identify the influence of data on LCA outcomes has enhanced during the last several years. Analyzes the dependability of the LCA results produced by these research.

- **Impact assessment**: This stage, known as life cycle impact assessment, covers the evaluation of environmental effect categories, classification, and characterization. For this process, the software integrates a variety of approaches, including CML, Recipe, CED, etc., [64]. This step connects the activities of a product's life cycle to specific environmental impacts.
- **Interpretation**: It comprises the study of the results gained at this stage, the identification of hot spots, and the improvement of environmental impacts by identifying the input or process on which to concentrate. The last step of the LCA should include the generation of findings and suggestions for decision-makers that are in line with the aim of the research as well as its scope.

4.1.2 LCC

LCC is defined as the total cost of ownership of an asset over its useful life [65]. It originally appeared in the US Department of Defense's acquisition and usage of military equipment [66]. When estimating the entire life cycle costs of a good, the LCC methodology incorporates the expenses of design, raw material procurement, operation, maintenance, and disposal [67]. Although it was a very old method, it has not yet reached its final level of development. The primary reason for this is the lack of a general standard that gives implementation recommendations for LCC [68]. The restricted directive is ISO 15686-5, which attempts to plan the useful life of buildings and constructed assets. Nevertheless, it is evident that norms and guidelines are required for LCC, which is a crucial instrument for the economic dimension, which is a pillar of sustainability.

4.1.3 S-LCA

S-LCA is a technique that may be adopted in many sizes, ranging from regional to national systems. It analyzes the social effects of goods and services across their lifespans [69]. It was designed in compliance with ISO 14040 and 14,044 standards and is based on the environmental LCA approach [70]. S-LCA focuses on the positive and negative impacts of a product, service, or organization on the well-being of individuals and society, the cultural inheritance, and the social conduct [71]. The S-LCA process consists of four basic steps: defining the purpose and scope of the study, compiling a life cycle inventory, conducting a life cycle impact analysis, and interpreting the results of the life cycle impact analysis.

There is no established standard for S-LCA, although there are guidelines developed by UNEP and the Society for Environmental Chemistry and Toxicology's Life Cycle Initiative (SETAC). UNEP/SETAC published the first version of the handbook and Methodological Sheets in 2009 [72]. Despite UNEP/SETAC's publication of S-LCA guidelines, the implementation of S-LCA in a methodological context is just in its beginning at this point [71, 73]. Two broad types of effect assessment methodologies were recommended in the updated version of the recommendations issued in 2021: the reference scale approach and the impact pathway approach [74]. In contrast, pathways of action methodologies examine social implications using characterization models with indicators comparable to LCA [71]. Using scoring methods to collect information based on the selected indications, the pathway of action technique attempts to evaluate the cause-and-effect chain. The life cycle inventory guide issued by UNEP/SETAC in 2021 identifies six stakeholder categories: workers/employees, local community, society, consumers, value chain actors, and children [74]. The subcategories of these stakeholder categories were also identified, as were the primary causes of the social impact. Each stakeholder type is associated with a set of indicators, and the S-LCA analysis is conducted using the information gathered by these indicators. UNEP/SETAC's indicators for the worker category include "freedom of association," "child labor," "fair salaries," "working hours," "forced labor," and "discrimination." Table 3 lists these stakeholders and their subcategories.

5 Environmental Pillar of Cotton Textile with LCA

5.1 Methodological Analysis

LCA applications in the textile industry are on the rise. Consequently, it is essential to analyze the LCA applications in the cotton supply chain due to the fact that the LCA technique demands extensive data and has distinct underlying assumptions. This section aims to contribute to the acceleration of application development in the cotton textile supply chain by highlighting the challenges associated with LCA applications.

The LCA process involves determining the analysis's objective and scope. An LCA research can be used to evaluate two or more goods or to find hotspots within a single product. Choosing the functional unit that will serve this role is the most

Table 3 Stakeholders and Indicators identified by UNEP/SETAC (*Indicators were added with revised version of Methodological Sheets in 2021) [74]

Worker	Local community	Value chain actors	Consumer	Society	Children
Freedom of association and collective bargaining	Access to material resources	Fair competition	Health and safety	Public commitment to sustainability issues	Education provided in the local community*
Child labor	Access to immaterial Resources	Promoting social responsibility	Feedback mechanism	Contribution to economic development	Health issues for children as consumers*
Fair salary	Delocalization and migration	Supplier Relationships	Privacy	Prevention and mitigation of armed conflicts	Children concerns regarding marketing practices*
Hours of work	Cultural heritage	Respect of intellectual property rights	Transparency	Technology development	
Forced labor	Safe and healthy living conditions	Wealth distribution	End-of-life responsibility	Corruption	
Equal opportunities/Discrimination	Respect of indigenous rights			Ethical treatment of animals*	
Health and safety	Community engagement			Poverty alleviation*	
Social benefit/Social security	Local employment				
Employment relationship*	Secure living conditions				
Sexual harassment*					
Smallholders including farmers*					

crucial decision at the outset of the investigation. Table 4 displays the functional units utilized in cotton supply chain LCA analyses.

Depending on the parameters of the investigation, a different functional unit will be chosen. When studying the agricultural stage of cotton, for instance, mass and area units were typically employed. Avadi et al. [20] designated the functional unit as 1 ton per hectare of seed cotton delivered at the farm gate, and 1 ton per hectare of baled cotton fiber and cottonseed sent to the gin [11]. Ullah et al. [75] chose based on kilograms of seed cotton [75]. Although it was usual practice to select the functional unit as mass throughout the cotton culture stage, the selection of a functional unit that demonstrates the unit's relationship with the area and ensures its inclusion in the yield total is still insufficient. Ultimately, the yield rate is contingent upon both the type of cotton farmed and the soil qualities of the country in which it is grown.

In LCA studies for the fiber stage, the unit of mass is typically chosen as the functional unit. The functional unit was established by Muthu et al. [77], Nguyen et al. [80] and Astudillo et al. [78] as 1 kg [77, 78, 80]. Similarly, Hedayati et al. [12] and Shen et al. [76], selected 1000 kg as the functional unit [12, 76]. In a recent study, [83] established that 1 hectare of cotton was the functional unit for fibers, despite the fact that there is consensus in the literature regarding this unit [83]. In addition, although there is agreement on the unit of mass, the amount chosen differs.

Even though the results produced for studies up to this point in the supply chain are more comparable, the clarity of this unit is essential for fabric and garment manufacturing. In the majority of published works, it is expressed as 1 kg of cloth [87, 88, 90]. According to [86], the functional unit value for cotton fabric is 10000 m and is also defined in kilograms [86]. Since fabric consumption in the textile supply chain is now reported in meters or square meters, this expression offers clearer information. According to [98], the unit expressed as 100% cotton blouse 146 g in weight, Standard Allowed Minutes 29.82 [98]. Zhang et al. [96] established that a T-shirt made of 100% cotton that had been knitted and colored, with short sleeves, weighed 153 g to be the functional unit [96]. Due to the fact that the garment's weight depends on the garment's size and design, including the mass weight to the piece/garment specification increases the transparency of LCA investigations [106]. The most difficult aspect of LCA studies for the cotton supply chain is standardizing the functional unit. Even if the chosen method is specified as mass, area, or length, it is necessary to include further clarifications in order to compare it with previous research.

A crucial aspect of the LCA technique is the analysis of cradle-to-grave implications. However, the majority of studies cannot cover every stage of the product's life cycle for numerous reasons. Although the absence of data is the primary cause for limited LCA investigations, time constraints also play a significant role. In the textile business, a cotton garment's life cycle begins with the sowing of cottonseed and continues to neighboring gins, which separate the lint and seed. Producing yarn from fibers that are subsequently formed into bales. These threads are transformed into textiles utilizing techniques such as weaving and knitting. Fabrics are used to manufacture clothing like pants and shirts. Following the production phase, the life cycle concludes with the retailing, use, and decommissioning stages.

Table 4 Functional unit of LCA studies for cotton textiles

Production stage	Functional unit	References
Seed cotton	Per kilogram of seed cotton (seed and lint together)	[75]
Seed cotton	Six functional units: 1 ton per hectare of seed cotton delivered at the farm gate, and 1 ton per hectare of baled cotton fiber and cottonseed sent to the gin	[11]
Fiber	1000 kg of staple fiber	[76]
Fiber	1 kg of fiber	[77]
Fiber	1 kg of raw silk	[78]
Fiber	1 metric ton of cotton fiber manufactured in a cotton manufacturing system and shipped at port	[79]
Fiber	1 kg of average Australian cotton lint	[80]
Fiber	1 t of cotton	[81]
Fiber	1000 kg of cotton lint	[82]
Fiber	1 hectare of cotton	[83]
Fiber and Yarn	1 kg of cotton fiber, and 1 kg of textile yarn	[84]
Yarn	1 kg of dyed cotton yarn	[31]
Yarn	1000 kg produced yarns which are used for weaving into the fabrics	[85]
Fabric	10,000 m of cotton fabric, which weighs 2000 kg	[86]
Fabric	1 kg of modal knitted fabric	[87]
Fabric	1 kg of textile waste	[88]
Fabric	1 kg of colored cotton yarn	[89]
Fabric	1 kg of 125 GSM plain weaved woven cotton fabric	[90]
Fabric	1 kg of hand-woven cotton-Khadi fabric	[91]
Fabric	1 kg of materials	[92]
Fabric	A curtain 1 kg in weight	[93]
Fabric	1 m of manufactured denim fabric weighing 638.2 g was approximately 1.5 square meters of denim fabric	[5, 6]
Garment	T-shirt made of 250 g of cotton, and jacket made of 500 g of polyester	[94]
Garment	1000 kg of cotton materials	[95]
Garment	1000 items of knitted and dyed cotton T-shirt with a total weight of 200 kg and 50 washing cycles at 60 °C temperature	[16]
Garment	100% cotton knitted dyed short-sleeved T-shirt 153 g in weight	[96]
Garment	1 kg of clothing over the lifetime	[97]
Garment	100% cotton blouse 146 g in weight, Standard Allowed Minutes 29.82	[98]
Garment	For the cotton T-shirt, 1 kg is the established functional unit. A typical T-shirt weighs around 0.125 kg	[99]

(continued)

Table 4 (continued)

Production stage	Functional unit	References
Garment	1000 pcs of shirts	[100]
Garment	Making a women's, size 34, regular denim pants according to the usual technical conditions observed by the Brazilian textile industry	[17]
Garment	A knitted cotton T-shirt with an average weight of 154 g and a lifetime of 44 washes	[101]
Use	250 g of clothing, washed and dried for 25 cycles	[102]
Use	3 kg of goods, 50 washing cycles	[103]
Use	1 kg of textiles	[104]
End of life	1000 kg of household textile waste	[105]

For the cotton farming stage, [107, 108], and Ullah et al. [109] established their boundaries from cradle to farm gate [75, 107, 108]. In contrast, [89, 110] picked cradle to gin gate for cotton fiber as their boundary [89, 110]. Gate-to-gate refers to LCA studies conducted particularly for any level of the supply chain, and its applicability is widespread in the literature. Choosing this analysis allows for a deeper examination of the targeted process. In addition, if the process evaluated in LCA studies including benchmarking represents a small portion of the product's total life cycle, it may not be possible to obtain reliable conclusions with substantial system limits. For instance, [5, 6, 105] conducted LCA studies with a gate-to-gate method by focusing solely on the disposal phase and the dyeing phase, respectively [5, 6, 105].

Schmutz et al. [101] incorporated the production stages of the T-shirt into their cradle-to-gate analysis, with a particular focus on the use phase for a cotton T-shirt [101]. Similarly, there are numerous cradle-to-grave LCA studies analyzing consequences through the fabric stage [5, 6, 91, 95]. As expected by the LCA methodology, cradle-to-grave LCA studies that address all processes from procuring the raw material to the conclusion of the product's life are uncommon [100, 111]. In the system boundaries methodology, certain researchers can examine transports as a distinct phase. In the research conducted by [16, 88, 89], for instance, transportation within the system's boundaries was treated as a separate phase [16, 88, 89].

Since the LCA approach requires voluminous data, the most typical data sources are industry-collected primary data and secondary data sources such as Ecoinvent, which are utilized when this data is unavailable. Other data sources are also utilized as inputs in LCA analyses. These are the cited technical sources, including reports, analyses, and the national database [17, 31]. As the textile and cotton sector is comprised of numerous international government entities such as United States Department of Agriculture (USDA) and non-governmental organizations (NGOs), it is not uncommon to find other data sources (Textile Exchange, Cotton 2040, National Cotton Council).

Various impact assessment methodologies have been proposed by LCA standards for analyzing environmental impacts. Figure 7 provides a summary of the impact categories determined by LCA studies in the cotton supply chain. The midpoint impact categories in this Figure utilized for simplification were categorized based on their degree of similarity. IPCC and CML were the most frequently utilized recommended methods for the GWP environmental category. Examining the 24 accessible LCA studies in the literature for the cotton supply chain revealed that 20 of them calculated midpoint impacts using methods such as CML, CED, USEtox, etc. (Fig. 7). In addition, [94] calculated direct greenhouse gas emissions including CO_2, NO_x, PMs, and SO_2 without using these methodologies [94]. CED was the most often used approach following GWP, and it displays the impacts of renewable (R CED) and non-renewable (NR CED) energy sources. Seven studies utilized the CED technique. EDIP, Eco-indicator'99, and ReCipe were further calculating methods described for textile industry in the literature. The impacts on water cannot be ignored while evaluating the cotton supply chain. Although there was no agreed-upon approach involving water, it was the primary focus of the researches. In these studies, [95] solely calculated the water footprint for cotton materials [95]. For the environmental impacts of water, the water use method by [5, 6, 75, 91], the water depletion method by [101], the Water resource depletion method by [84], and the water consumption method were utilized [5, 6, 75, 84, 87, 91, 101]. In addition, [78] computed the blue water footprint and ruled out alternatives such as gray water [78]. It would be advantageous for the textile sector to employ a standardized method to quantify the environmental implications of water to make straightforward comparisons. The selection of midpoint and endpoint environmental effects potentials contained in the existing techniques of impact assessment is an additional crucial factor. Although it was stated that it is normally picked for the selected environmental effect category because it is relevant to the textile industry, the actual repercussions are typically rather distinct.

Due to the relevance of climate change, the GWP stood out in the category of moderate impacts. GWP category with different expressions such as greenhouse effect by [89] and climate change by [17, 12, 85, 88] were utilized for this potential [12, 17, 85, 88, 89]. Although several researchers, such as [16, 77], chose acidification potential, [85] utilized terrestrial acidification, and Mahdei et al. [83] used aquatic acidification potential [16, 77, 83, 85]. Eutrophication was among the most commonly utilized categories in textile LCA research [77, 89, 100]. Baydar et al. [16] used terrestrial and aquatic eutrophication potential in their LCA analysis of cotton T-shirts [16]. Zhang et al. [96] only assessed the aquatic eutrophication potential category, but Avadi et al. [20] calculated both freshwater and terrestrial eutrophication [11, 96]. Marine eutrophication was another infrequently evaluated category. Land use, despite being a crucial category for cotton, had received very little attention in LCA analyses. This category, which has been examined by [76, 89], Avadi et al. [20], was utilized by Mahdei et al. [83] as land occupancy [76, 83, 89]. In contrast, [78] divided this category into two subcategories: agricultural and urban land occupation [78]. The potential for human toxicity was another less common category. A few scholars have used this category in LCA studies [76, 84, 91]. In contrast, Avadi et al. [20] divided this category into human toxicity-cancer and human toxicity-non-cancer. In cotton supply chain LCA research, categories such as heavy metals, pesticides,

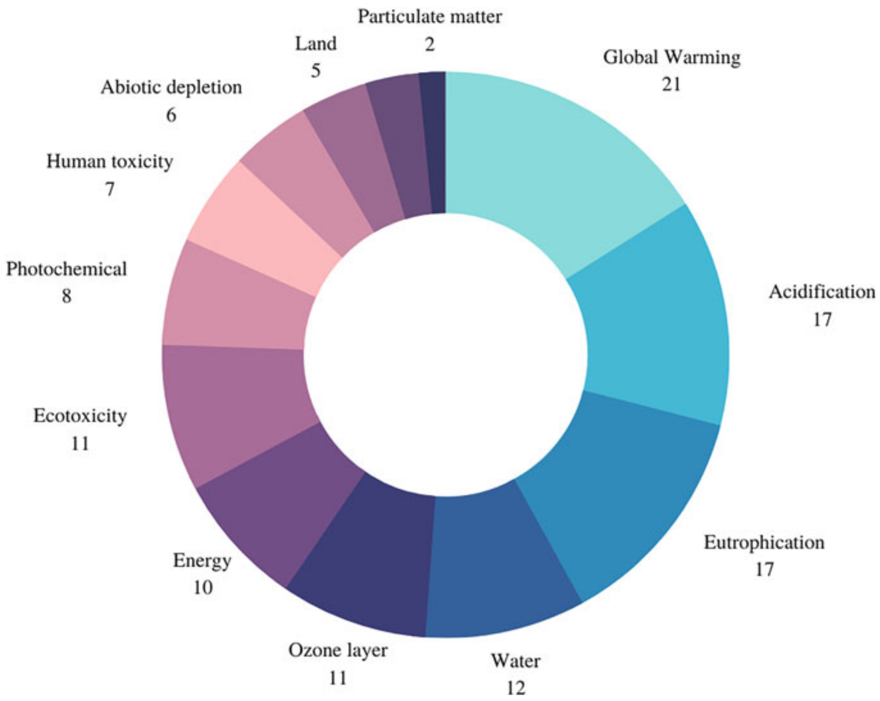


Fig. 7 The number of uses of the impact categories in selected LCA studies

ecological scarcity, winter and summer smog, carcinogenics, and fossil depletion were rarely addressed [31, 77, 85, 101]. Consequently, the categories utilized in the environmental impact evaluation of cotton-containing textiles varied considerably. Additionally, studies appeared to concentrate on environmental influences. Although the objective of the LCA technique is to calculate all environmental consequences, the limited category selection was chosen for the ease of the calculation processes. The most significant issue with the impact categories is the difficulty to compare them due to their variety of options.

5.2 Content Analysis

The LCA investigations yielded outcomes closely connected to the evaluation methodology selected. However, not only these selections but also the diversity of the substance of the research are essential for the development of the methodology and, eventually, the fight against environmental issues. Local, regional, national, continental, and global geographical limits and conditions chosen while implementing LCA are significant factors in the variation in outcomes. This information indicates the geographic region to which the data belongs. Terinte et al. [87] and Shen et al. [76], as examples of continental expression studies, determined environmental impacts for Europe and Western Europe, respectively [76, 87]. Figure 8 depicts the rates of utilizing continents as geographical borders. Examining the available studies in the literature regarding the cotton supply chain reveals that the geographical limit of 45% was in Asia. Europe came in second with 29%, followed by North America with 10%.

China and India were notably prominent on the Asian continent. As the two leading cotton-producing nations in the world, this outcome was predictable. While [78] conducted an LCA for fiber, [31] investigated cotton yarn on this continent [31, 78]. Moreover, [91, 94] conducted LCA for the production of cloth and apparel in this continent, respectively [91, 94]. Concerning studies conducted in China, examples include [85, 96] for garment and yarn research, respectively [85, 96]. Although the United States and Brazil were the other two major producers of cotton, very few research have been conducted in these countries. Despite the existence of research by [17, 76], there is still a need for improvement [17, 76]. Cotton LCA studies in Europe regularly encountered the geographical boundaries of Spain [89, 95]. Turkey was also a prominent country for LCA research in Asia [5, 6, 16, 100].

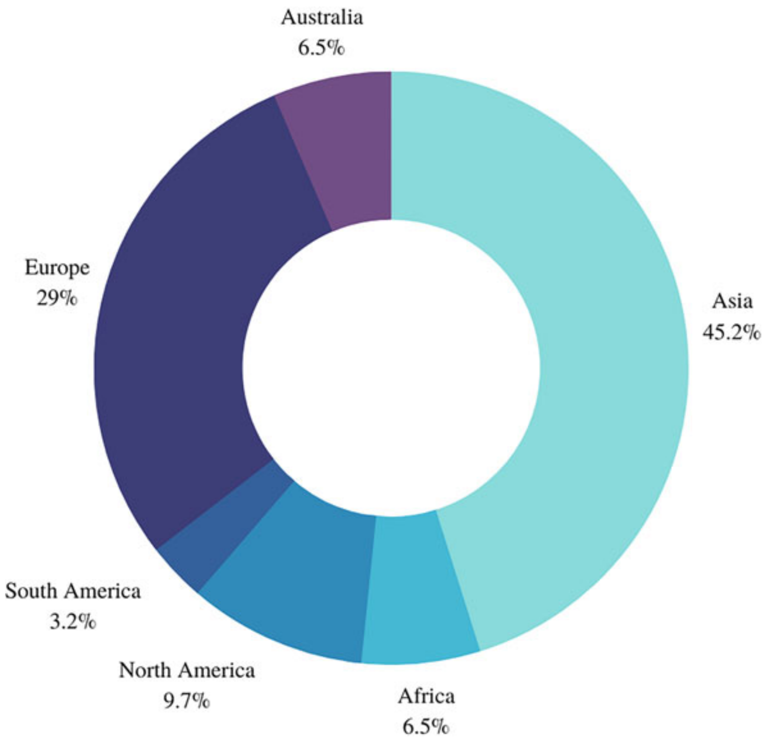


Fig. 8 Geographical boundaries of textile LCA studies

Table 5 Cotton fiber type in the LCA studies

Cotton type	References
Conventional cotton jean trousers	[17]
Conventional cotton cropping systems	[75]
Conventional dyed cotton yarn	[31]
Conventional cotton fiber	[79]
Conventional cotton fiber	[83]
Conventional cotton fiber	[80]
Conventional cotton T-shirt	[81]
Conventional cotton fiber and yarn	[84]
Conventional cotton T-shirt	[99]
Conventional cotton T-shirt	[101]
Conventional, BCI, organic cotton seed	[13]
Better Cotton, Conventional Cotton, and Organic Cotton	[112]
Cotton made in Africa	[113]
Conventional, organic, and recycled cotton T-shirt	[100]
organic and conventional non-Bt cotton	[11]
Recycled cotton yarn	[85]
Conventional and recycled cotton denim fabric	[5, 6]
Organic, Conventional, Recycled cotton yarn	[89]
Conventional and Organic cotton T-shirt	[16]
Organic cotton fiber	[114]

There is a daily increase in the value of eco-friendly cotton options in the textile industry. It is important to discover these various cotton projects that aim to be more environmentally friendly by employing the scientifically significant LCA method. The literature reviews are organized by cotton type in Table 5.

Shah et al. [13] measured the environmental advantages of organic and BCI seed cotton production in comparison to conventional seed cotton production using LCA [13]. C&A [112] conducted another study exposing the environmental implications of BCI cotton [112]. Sphera [113] conducted the only LCA research for Cotton made in Africa, which was published as a report [113]. There were considerably more studies concerning organic cotton, the most important sustainable cotton. C&A [112], Avadi et al. [20], TE [114], and [13] conducted organic cotton LCA studies for cotton fiber, [89] for organic yarn, and [16, 100] for organic clothing [11, 13, 16, 89, 100, 112, 114]. The growing interest in recycled cotton in recent years has led to the creation of publications in this sector. While [85, 89] conducted LCAs for recycled cotton yarn, [5, 6] did so for recycled cotton denim fabric [5, 6, 16, 89, 85] Kazan et al. [100] conducted an LCA for a T-shirt constructed from recycled cotton [16, 100].

The majority of research on the cotton supply chain has been on conventional cotton. Although sustainable cotton varieties are on the agenda of the textile industry, very few LCA studies have been conducted in this field. Although the number of LCA studies for organic and recycled cottons was increasing daily, these studies are required for other sustainable cotton systems, such as ABRAPA, BASF e3, and Fairtrade. In addition, LCA studies for clothing according to different types of cotton were confined to jeans and T-shirts; it is crucial that these studies be conducted on additional textile types.

6 Economic Pillar with LCC

LCC has been utilized for a great number of years as a well-established procedure; nonetheless, it has only recently emerged as an element of the examination of sustainability [115]. On the other hand, it is almost completely useless in any stage of the cotton textile production process. Following the completion of a literature study for LCC studies, it was discovered that roughly two-thirds of the articles in the published research were from the construction industry [116]. The lack of official or standardized guidelines for implementation across different businesses was the key factor contributing to this situation. The implementation of LCC, in addition to LCA using software that is often used for LCA, contributed to the simplification of the system. For example, Ciroth and Franze (2009) have created a documentation for integrating LCC with the Simapro Software [117]. It is required to construct the LCC technique as there are no software embedded methods such as LCA due to the lack of software embedded methods. The strategy consists of a number of steps, the most important of which are characterization, damage assessment, normalization, and weighting.

The second stage, following the creation of the method, is to add the cost per unit for the inputs. The software completes the calculation utilizing methodologies and costs. Using this technique, [5, 6] conducted LCC for an indigo warp dyeing containing 60% cotton. Despite the exclusion of the construction, occupation, and maintenance stages due to the comparative nature of the study, their contributions to the methodology were significant [5, 6]. According to the LCC results, the green rope dyeing technique had a much greater LCC (57%) than the other processes. This outcome demonstrated the significance of LCC studies in evaluations of holistic sustainability assessment. A product deemed more sustainable based on LCA results may not be practical due to its greater cost. It is therefore critical that LCC studies be included in the sustainability assessment.

Hall [118] carried out a life cycle cost (LCC) assessment study on a T-shirt that was produced in India and exported to the United States in order to demonstrate and develop the approach, as well as to evaluate and contrast it with other methodologies [118]. They did this by incorporating social and environmental concerns into the cost of commodities, and they called this concept the sustainability price. They gave a presentation to identify the data sources and design the solution, which was essential for the data deficit issue with the LCC application. Rather than in the process of cutting and sewing T-shirts, the production of cotton appears to be where the living wage gap has the greatest influence, according to the findings of the study.

7 Social Pillar of Cotton Textile with S-LCA

In the current review of the cotton life cycle, the number of studies including a social dimension into the life cycle method was extremely low. Principally because the method is still in its infancy. Due to the qualitative and subjective nature of social behaviors, it is difficult to collect data and susceptible to subjective evaluation. Table 6 provides a review of the studies that have been conducted on the cotton supply chain.

S-LCA analysis of organic cotton growing in Turkey is included in a recent master's thesis on cotton farming [119]. Employees, participants in the value chain, and the neighborhood all received attention from UNEP/SETAC. The study used a reference scale approach to analyze the processes involved in growing organic cotton and making denim. Cotton farming and fabric manufacturing were given the lowest grade (+1) because their analysis did not provide conclusive evidence of widespread use of child labor in those industries. The harvest, which necessitates the greatest number of worker hours for cotton planting, poses the greatest possible social impact risk with respect to work schedules, working conditions, and compensation and benefits. Massive social impact risks associated with fabric manufacturing include inadequate salaries, overwork, and unsafe working conditions.

Garcia et al. [121] conducted another S-LCA analysis for the jean supply chain using combined social and environmental LCA approach (SELCA) [121]. According to their study, the majority of the social impact stemmed from the global textile supply chain, particularly cotton cultivation, fabric weaving, and garment assembly, where the impact on workers was greatest. Although SELCA was a novel tool, they demonstrated that it is useful for identifying and enhancing social performance throughout the jeans life cycle. Nevertheless, it has been asserted that the utilization of the functional unit and the determination of its role in the distribution of social influence is the most significant issue in the social dimension.

Commonly, existing standards are utilized to generate a performance benchmark for site-specific evaluation. Conventions of the International Labour Organization (ILO), ISO 26000, and ISO 14001, as well as certificates such as BSCI, SA8000, and Occupational Safety and Health Administration (OSHA) Standards are examples. Fidan et al. [5, 6] conducted a gate-to-gate S-LCA research for the warp dyeing process utilized in the production of denim fabric containing 60% cotton [5, 6]. The company-specific application of these criteria has been particularly implemented during site-specific evaluation. According to earlier UNEP/SETAC methodological sheets with a subcategory assessment method (SAM), all stakeholders and relevant subcategories were analyzed. In their study, due to the difficulty in attaching the S-LCA to the functional unit, it was divided into functional units based on the number of working hours associated with the functional unit (WFU) in order to compare the two processes [124]. They followed [125] in combining the S-LCA evaluation results for each subcategory into a single value [125]. They mentioned the absence of LCA-related databases and the need to establish a relationship with the functional unit.

Table 6 A summary of S-LCA studies for cotton textiles

Impact assessment method	Stakeholder	System boundary	Content	Geographical boundary	References
The reference scale approach	Worker, Value chain actors, and local community	Cradle to gate	Organic cotton cultivation and fabric	Turkey	[119]
Social hotspots analysis with PILCA; site-specific social assessment	Workers, local communities, value chain actors, society	Cradle to gate	Shirt made of 97% cotton and 3% elastane	China, Malaysia, Bangladesh, Myanmar, The Netherlands	[120]
SELCA	Worker	Cradle to cradle	Jeans made with 100% virgin cotton and 40% recycled cotton	Holland	[121]
SAM	All	Gate to gate	Cotton warp dyeing 60% cotton and 40% lyocell	Turkey	[5, 6]
SHDB	NA	Cradle to gate	Textile consumption	Sweden	[92]
Socioeconomic costs	Worker	Cradle to gate	T-shirts; jeans	USA–Europe, India–Bangladesh, China	[122]
SHDB	All	Cradle to gate	Textile supply chain	Angola, Argentina, Bangladesh, Brazil, China, Algeria, Ghana, Equatorial Guinea, Indonesia, India, Iran, Italy, Japan, South Korea, Mexico, Mozambique, Pakistan, Russia, East Timor, Turkey, Taiwan, Uzbekistan	[123]

In addition, databases for assessing the social dimension's impact have been compiled in the research that has been done thus far. The Social Hotspot Database (SHDB) ensures information on prospective social risk levels (low, medium, high, and extremely high) in various industries and geographic locations, and is essential for adding social components associated with background activities. In contrast, the PSILCA database provides an indicator of the principal societal risks through macro-level statistics. As activity variables, S-LCA rules advise working hours or value added. Roos et al. [92], for instance, conducted an S-LCA utilizing the questionnaire established by [92, 123]. Using the database supplied by the Global Trade Analysis Project, they determined the social impact of the $1 clothes market in Sweden. The results enabled the identification of negative social hotspots for the Swedish apparel industry at the industry sector level, thereby shedding light on the sector's current social performance. In the textile and garment business, the concept of social hotspots revealed major social risks associated with salaries, child labor, and exposure to carcinogens in the workplace. According to the country's minimum wage, the hazards of wage below 2 USD, Low average wage, and child labor were the most severe. In the absence of data, assessing the effect of actions undertaken to reach the desired degree of sustainability on the realization of social sustainability goals has proven to be the most challenging. Zamani et al. [123] identified social nodes along the production chain for 11 consumer-selected indicators of social status in the process of making clothes [123]. The working hours of country-specific sectors with high and very high risk levels were combined to determine the severity of each social indicator. The longest-lasting of the eleven analyzed risk factors was paying workers less than $2 per day. In the sensitivity analysis performed for the cutting system, rates between 1 and 4% were evaluated. They discovered that the choice of cutting rule influenced the amount of country-specific sectors included in the manufacturing system, and that a 2% cutting rule could be used to include these sectors. While this would result in too many units to be managed, as studies without the application of the cutoff rule would yield too many country-specific sectors with high or extremely high risk levels, it is less significant because many of these units have to do with extremely few working hours throughout the entire supply chain. In S-LCA studies, it was essential to apply the cutting rule. Herrera Almanza [120] utilized the PILSA database to comprehend the accomplishment in social context of a shirt and its prospective contribution to SDGs [120]. Macro-level information was obtained from PILSA in order to conduct the evaluation of a shirt whose distribution network spanned five countries, from cotton cultivation in China through selling in the Netherlands. As a result of the investigation, it was suggested that the Dutch corporation create an environmental management system and enhance its social management. It was suggested that the company's suppliers ensure that the cotton spinning company in China and the shirt producer in Malaysia adhere to international standards for weekly working hours, extra hours, associational freedom, women's rights, and trash disposal procedures. In addition, the socioeconomic costs technique necessitates the valuation of external socioeconomic costs applied in the literature. Minimum acceptable wage (as a particular element of fair wage), child labor, absolute poverty, long working hours, and workplace health and safety were subcategories of the technique suggested by van der Velden and Vogtlander [122]. They discovered that the social hotspots of the manufacturing chain for six typical textile goods were the Indian cotton fields and the Bangladeshi garment factories.

8 Present and Future of Life Cycle Sustainability Assessment in the Textile Industry

Numerous environmental, social, and economic issues have been identified as priorities for the textile industry. Cotton, however, is a new area of focus for sustainable development initiatives. Cotton has been the major bio-based fiber in the business since the beginning of recorded history, making it the key pioneer in this shift. Presently, pCotton production, which includes eco-friendly cotton farming, stands at 30% and is steadily increasing. Effective resource management relies heavily on the application of evaluation methods. All three of these acronyms—LCA, S-LCA, and LCC—represent three of the most important partners in the industrial world when it comes to growth and transformation. Studies that have reached the level of maturity for LCA, S-LCA, and LCC application are in their infancy. For LCA, use and end-of-life alternatives have been the topic of numerous LCA studies, along with products such as yarn, fabric, and garment, which are almost the cotton supply chain's intermediate raw materials. However, the first issue with LCA in textiles is the uniformity of the functional unit that is being evaluated. The usage of different units makes comparisons difficult. Another difficulty is maintaining reliable data throughout the production process. As a result, future LCA studies will require uncertainty and sensitivity evaluations for data uncertainty. One more complication in the cotton supply chain is the large number of LCIA methods. No matter how narrowly the existing procedures attempt to address a given environmental impact, the vastly different approaches to calculation made any such comparisons between them impossible. The geographic scope of future LCA investigations needs to be clearly established. The diversity in soil types and available resources among cotton-growing regions makes it important to maintain a wide perspective. S-LCA studies of the textile industry are infrequent. In the past, many authors have tried and failed to use the S-LCA in their work. The biggest problem in practice is figuring out how to define the functional unit's goals and how it should affect the distribution of social consequences. One of the key reasons why the S-LCA is not implemented to the needed degree is because there is a lack of data. Despite the fact that there are a lot of databases out there, they are not yet at the required level. As a result of this lack of data, the definition of system boundaries, the selection of stakeholders, and the determination of indicators are all affected. In spite of the fact that the vast majority of the existing research concentrates on the employees, it is imperative that any future investigations look into the other stakeholders as well. Because the S-LCA approach does not have the sensitivity necessary to adequately reflect social repercussions, the requirement of developing the method is a second important factor to consider. In addition, for many different social indicators, it is necessary to expand the work on defining social objectives and accomplishment standards in order to meet the requirements. Several steps need to be performed in order to raise the rate of S-LCA utilization all the way through the cotton supply chain. It is strongly proposed that both the development of the methodology and the establishment of databases be prioritized, as the use of the LCC approach in the cotton supply chain is almost nonexistent. Developing sub-methodologies for LCSA studies that examine various strategies collectively is an important step that needs to be taken in order to study the triple bottom line. It was also recommended that more in-depth investigations on LCSA be carried out so that appropriate decisions can be made [126]. This chapter gives vital information to the cotton industry, decision-makers, and scientists addressing the approaches and components for strengthening the cotton supply chain's capacity to be environmentally friendly.

References

1. Hansen EG, Schaltegger S (2013) 100 per cent organic? A sustainable entrepreneurship perspective on the diffusion of organic clothing. Corp Gov
2. Grand View Research (2021) Textile market size, share & trends analysis report by raw material (Cotton, Wool, Silk, Chemical), by product (Natural Fibers, Nylon), by application (Technical, Fashion), by region, and segment forecasts, 2022–2030
3. Remy N, Speelman E, Swartz S (2016) Style that's sustainable: a new fast-fashion formula. McKinsey Global Institute
4. Desore A, Narula SA (2018) An overview on corporate response towards sustainability issues in textile industry. Environ Dev Sustain 20:1439–1459
5. Fidan FŞ, Aydoğan EK, Uzal N (2021a) An integrated life cycle assessment approach for denim fabric production using recycled cotton fibers and combined heat and power plant. J Clean Prod 287:125439
6. Fidan FŞ, Aydoğan EK, Uzal N (2021b) Multi-dimensional sustainability evaluation of indigo rope dyeing with a life cycle approach and hesitant fuzzy analytic hierarchy process. J Clean Prod 309:127454
7. Becker HA (2001) Social impact assessment. Eur J Oper Res 128:311–321
8. Rieple A, Singh R (2010) A value chain analysis of the organic cotton industry: the case of UK retailers and Indian suppliers. Ecol Econ 69:2292–2302
9. Ortega-Egea JM, García-de-Frutos N (2019) Greenpeace's detox campaign: towards a more sustainable textile industry. In: Case studies on social marketing. Springer, pp 37–47
10. Shen B, Wang Y, Lo CK, Shum M (2012) The impact of ethical fashion on consumer purchase behavior. J Fash Mark Manag Int J
11. Avadí A, Marcin M, Biard Y, Renou A, Gourlot J-P, Basset-Mens C (2020) Life cycle assessment of organic and conventional non-Bt cotton products from Mali. Int J Life Cycle Assess 25:678–697
12. Hedayati M, Brock PM, Simmons AT (2015) Consequential LCA in cotton production systems: opportunities and challenges. In: The 1st Australian conference on life cycle assessment for agriculture and food, Melbourne, 23rd–24th November
13. Shah P, Bansal A, Singh RK (2018) Life cycle assessment of organic, BCI and conventional cotton: a comparative study of cotton cultivation practices in India. In: Designing sustainable technologies, products and policies. Springer, Cham, pp 67–77
14. Agnhage T, Perwuelz A, Behary N (2017) Towards sustainable Rubia tinctorum L. dyeing of woven fabric: how life cycle assessment can contribute. J Clean Prod 141:1221–1230

15. Barcelos SM, Luz LM, Vasques RS, Piekarski CM, Francisco AC (2013) Introductory background for Life Cycle Assessment (LCA) of pure silk fabric. Indep J Manag Prod 4:170–187
16. Baydar G, Ciliz N, Mammadov A (2015) Life cycle assessment of cotton textile products in Turkey. Resour Conserv Recycl 104:213–223
17. Morita AM, Moore CCS, Nogueira AR, Kulay L, da Silva Sá Ravagnani MA (2020) Assessment of potential alternatives for improving environmental trouser jeans manufacturing performance in Brazil. J Clean Prod 247:119156
18. Roos S, Sandin G, Zamani B, Peters G (2015) Environmental assessment of Swedish fashion consumption. Five garments–sustainable Futures. Mistra Future Fash
19. Pollok L, Spierling S, Endres H-J, Grote U (2021) Social life cycle assessments: a review on past development, advances and methodological challenges. Sustainability 13:10286
20. Zamagni A, Pesonen H-L, Swarr T (2013) From LCA to life cycle sustainability assessment: concept, practice and future directions. Int J Life Cycle Assess 18:1637–1641
21. Andrews ES (2009) Guidelines for social life cycle assessment of products: social and socio-economic LCA guidelines complementing environmental LCA and Life Cycle Costing, contributing to the full assessment of goods and services within the context of sustainable development. UNEP/Earthprint
22. Arcese G, Lucchetti MC, Massa I, Valente C (2018) State of the art in S-LCA: integrating literature review and automatic text analysis. Int J Life Cycle Assess 23:394–405
23. Benoît Norris C, Traverzo M, Neugebauer S, Ekener E, Schaubroeck T, Russo Garrido S (2020) Guidelines for social life cycle assessment of products and organizations 2020
24. United Nation (2015) Sustainable development goals
25. Grand View Research (2022) Global textile market size & share report, 2022–2030
26. Textile Exchange (2021a) Preferred fiber & materials market report
27. USDA (2022a) Cotton: world markets and trade
28. OECD/FAO (2021) OECD-FAO agricultural outlook 2021–2030. OECD Publishing, Paris
29. USDA (2022b) Cotton supply and distribution by country 2021/22
30. Chapagain AK, Hoekstra AY, Savenije HH, Gautam R (2006) The water footprint of cotton consumption: an assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries. Ecol Econ 60:186–203
31. Bevilacqua M, Ciarapica FE, Mazzuto G, Paciarotti C (2014) Environmental analysis of a cotton yarn supply chain. J Clean Prod 82:154–165
32. Bärlocher C, Gujja B, Holland R (2020) The impact of cotton on freshwater resources and ecosystems
33. Cotton Up (2021) Cotton challenges
34. FAO I (2015) Measuring sustainability in cotton farming systems: towards a guidance framework, Rome. Accessed 05 July 18
35. Burguburu A, Tanné C, Bosc K, Laplaud J, Roth M, Czyrnek-Delêtre M (2022) Comparative life cycle assessment of reusable and disposable scrub suits used in hospital operating rooms. Clean Environ Syst 4:100068
36. Scheffer MR (2001) A sustainable vision on the cotton industry after 2005. Proc Speech Held Gen Assem EUROCOTON Bruss Belg 30
37. Clay J (2013) World agriculture and the environment: a commodity-by-commodity guide to impacts and practices. Island Press
38. Ismail SA, Chen G, Baillie C, Symes T (2011) Energy uses for cotton ginning in Australia. Biosyst Eng 109:140–147
39. ILO (2022) Agriculture; plantations; other rural sectors
40. ILO (2018) The Rana Plaza Accident and its aftermath
41. CFDA (2022) Cotton
42. Textile Exchange (2020) 2025 sustainable cotton challenge: second annual report 2020.
43. Textile Exchange (2021b) 2025 sustainable cotton challenge third annual report 2021
44. Tsoulfas GT, Pappis CP (2006) Environmental principles applicable to supply chains design and operation. J Clean Prod 14:1593–1602

45. Fidan FŞ (2021) Holistic sustainability assessment with the life cycle analysis approach in the denim sector (Doctorate). Erciyes University
46. Meadows DH, Meadows DL, Randers J, Behrens III, WW (1972) The limits to growth-club of Rome
47. Nations U (1972) Report of the United Nations conference on the human environment
48. Brundtland GH (1987) Our common future: report of the world commission on environment and development. United Nations Comm 4(1):300
49. Gladwin TN, Kennelly JJ, Krause T-S (1995) Shifting paradigms for sustainable development: implications for management theory and research. Acad Manage Rev 20:874–907
50. Weiss EB (1992) United Nations conference on environment and development. Int Leg Mater 31:814–817
51. UNFCCC (1997) Kyoto protocol
52. Summit M (2000) United Nations millennium declaration. U Nations Ed
53. Waage J, Banerji R, Campbell O, Chirwa E, Collender G, Dieltiens V, Dorward A, Godfrey-Faussett P, Hanvoravongchai P, Kingdon G (2010) The millennium development goals: a cross-sectoral analysis and principles for goal setting after 2015: Lancet and London international development centre commission. lancet 376:991–1023
54. Sibley A (2007) World Summit on Sustainable Development (WSSD), Johannesburg, South Africa. Encyclopedia of earth, Washington, D.C. Environmental information coalition, national council for science, and the environment. Last revised October
55. WHO (2012) United nations conference on sustainable development
56. General Assembly Resolution (2015) 70/1, transforming our world: the 2030 agenda for sustainable development, Geneva U. N
57. BM (2015) Paris agreement. In: Report of the Conference of the parties to the United Nations framework convention on climate change (21st Session, 2015: Paris). Retrieved December. HeinOnline, p 2017
58. Elkington J, Rowlands IH (1999) Cannibals with forks: the triple bottom line of 21st century business. Altern J 25:42
59. Kloepffer W (2008) Life cycle sustainability assessment of products. Int J Life Cycle Assess 13:89–95
60. ISO, 2006a. 14040. Environmental management. Cycle assessment—Principles and framework, pp 235–248
61. ISO (2006b) 14044. Environmental management. Life cycle assessment. Requirements and guidelines, vol 14044
62. Pauer E, Wohner B, Tacker M (2020) The influence of database selection on environmental impact results. Life cycle assessment of packaging using gabi, ecoinvent 3.6, and the environmental footprint database. Sustainability 12:9948
63. Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B (2016) The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 21:1218–1230
64. Das SC, La Rosa AD, Grammatikos SA (2022) Life cycle assessment of plant fibers and their composites. In: Plant fibers, their composites, and applications. Elsevier, pp 457–484
65. Woodward DG (1997) Life cycle costing—theory, information acquisition and application. Int J Proj Manag 15:335–344
66. Shaked S, Crettaz P, Saade-Sbeih M, Jolliet O, Jolliet A (2015) Environmental life cycle assessment. CRC Press
67. Hunkeler D, Lichtenvort K, Rebitzer G (2008) Environmental life cycle costing. CRC Press
68. França WT, Barros MV, Salvador R, de Francisco AC, Moreira MT, Piekarski CM (2021) Integrating life cycle assessment and life cycle cost: a review of environmental-economic studies. Int J Life Cycle Assess 26:244–274
69. Di Cesare S, Silveri F, Sala S, Petti L (2018) Positive impacts in social life cycle assessment: state of the art and the way forward. Int J Life Cycle Assess 23:406–421
70. Ekener E (2015) State of the art on social LCA
71. Sala S, Vasta A, Mancini L, Dewulf J, Rosenbaum E (2015) Social life cycle assessment: state of the art and challenges for supporting product policies. JRC Tech Rep

72. Benoît-Norris C, Vickery-Niederman G, Valdivia S, Franze J, Traverso M, Ciroth A, Mazijn B (2011) Introducing the UNEP/SETAC methodological sheets for subcategories of social LCA. Int J Life Cycle Assess 16:682–690
73. UNEP/SETAC (2020) Guidelines for social life cycle assessment of products and organizations 2020. UN Environment Programme ISBN 978-92
74. UNEP/SETAC (2021) The methodological sheets for subcategories in social life cycle assessment (S-LCA). UNEPSETAC Life Cycle Initiative Ghent Belgium, pp 1–152
75. Ullah A, Perret SR, Gheewala SH, Soni P (2016) Eco-efficiency of cotton-cropping systems in Pakistan: an integrated approach of life cycle assessment and data envelopment analysis. J Clean Prod 134:623–632
76. Shen L, Worrell E, Patel MK (2010) Environmental impact assessment of man-made cellulose fibres. Resour Conserv Recycl 55:260–274
77. Muthu SS, Li Y, Hu JY, Mok PY (2012) Quantification of environmental impact and ecological sustainability for textile fibres. Ecol Indic 13:66–74
78. Astudillo MF, Thalwitz G, Vollrath F (2014) Life cycle assessment of Indian silk. J Clean Prod 81:158–167
79. Hedayati M, Brock PM, Nachimuthu G, Schwenke G (2019) Farm-level strategies to reduce the life cycle greenhouse gas emissions of cotton production: an Australian perspective. J Clean Prod 212:974–985
80. Nguyen QV, Wiedemann SG, Simmons A, Clarke SJ (2021) The environmental consequences of a change in Australian cotton lint production. Int J Life Cycle Assess 26:2321–2338
81. Zhang T, Zhai Y, Ma X, Shen X, Bai Y, Zhang R, Ji C, Hong J (2021) Towards environmental sustainability: life cycle assessment-based water footprint analysis on China's cotton production. J Clean Prod 313:127925
82. Chen F, Ji X, Chu J, Xu P, Wang L (2021) A review: life cycle assessment of cotton textiles. Ind Textila 72:19–29
83. Mahdei KN, Esfahani SMJ, Lebailly P, Dogot T, Van Passel S, Azadi H (2022) Environmental impact assessment and efficiency of cotton: the case of Northeast Iran. Environ Dev Sustain 1–21
84. La Rosa AD, Grammatikos SA (2019) Comparative life cycle assessment of cotton and other natural fibers for textile applications. Fibers 7:101
85. Liu Y, Huang H, Zhu L, Zhang C, Ren F, Liu Z (2020) Could the recycled yarns substitute for the virgin cotton yarns: a comparative LCA. Int J Life Cycle Assess 25:2050–2062
86. Yuan ZW, Zhu YN, Shi JK, Liu X, Huang L (2013) Life-cycle assessment of continuous pad-dyeing technology for cotton fabrics. Int J Life Cycle Assess 18:659–672
87. Terinte N, Manda BK, Taylor J, Schuster KC, Patel MK (2014) Environmental assessment of coloured fabrics and opportunities for value creation: spin-dyeing versus conventional dyeing of modal fabrics. J Clean Prod 72:127–138
88. Dahlbo H, Aalto K, Eskelinen H, Salmenperä H (2017) Increasing textile circulation—consequences and requirements. Sustain Prod Consum 9:44–57
89. Esteve-Turrillas FA, de La Guardia M (2017) Environmental impact of recover cotton in textile industry. Resour Conserv Recycl 116:107–115
90. Linhares T, de Amorim MTP (2017) LCA of textile dyeing with Acacia Dealbata tree bark: a case study research. Procedia Eng 200:365–369
91. Bhalla K, Kumar T, Rangaswamy J (2018) An integrated rural development model based on comprehensive Life-Cycle Assessment (LCA) of Khadi-Handloom Industry in rural India. Procedia CIRP 69:493–498
92. Roos S, Zamani B, Sandin G, Peters GM, Svanström M (2016) A life cycle assessment (LCA)-based approach to guiding an industry sector towards sustainability: the case of the Swedish apparel sector. J Clean Prod 133:691–700
93. Yasin S, Behary N, Perwuelz A, Guan J (2018) Life cycle assessment of flame retardant cotton textiles with optimized end-of-life phase. J Clean Prod 172:1080–1088
94. Steinberger JK, Friot D, Jolliet O, Erkman S (2009) A spatially explicit life cycle inventory of the global textile chain. Int J Life Cycle Assess 14:443–455

95. Chico D, Aldaya MM, Garrido A (2013) A water footprint assessment of a pair of jeans: the influence of agricultural policies on the sustainability of consumer products. J Clean Prod 57:238–248
96. Zhang Y, Liu X, Xiao R, Yuan Z (2015) Life cycle assessment of cotton T-shirts in China. Int J Life Cycle Assess 20:994–1004
97. Moazzem S, Daver F, Crossin E, Wang L (2018) Assessing environmental impact of textile supply chain using life cycle assessment methodology. J Text Inst 109:1574–1585
98. Muthukumarana TT, Karunathilake HP, Punchihewa HKG, Manthilake M, Hewage KN (2018) Life cycle environmental impacts of the apparel industry in Sri Lanka: analysis of the energy sources. J Clean Prod 172:1346–1357
99. Li X, Chen L, Ding X (2019) Allocation methodology of process-level carbon footprint calculation in textile and apparel products. Sustainability 11:4471
100. Kazan H, Akgul D, Kerc A (2020) Life cycle assessment of cotton woven shirts and alternative manufacturing techniques. Clean Technol Environ Policy 22:849–864
101. Schmutz M, Hischier R, Som C (2021) Factors allowing users to influence the environmental performance of their T-shirt. Sustainability 13:2498
102. Kim J, Yun C, Park Y, Park CH (2015) Post-consumer energy consumption of textile products during 'use'phase of the lifecycle. Fibers Polym 16:926–933
103. Yun C, Patwary S, LeHew ML, Kim J (2017) Sustainable care of textile products and its environmental impact: tumble-drying and ironing processes. Fibers Polym 18:590–596
104. Laitala K, Klepp IG, Henry B (2018) Does use matter? Comparison of environmental impacts of clothing based on fiber type. Sustainability 10:2524
105. Zamani B, Svanström M, Peters G, Rydberg T (2015) A carbon footprint of textile recycling: a case study in Sweden. J Ind Ecol 19:676–687
106. Moazzem S, Crossin E, Daver F, Wang L (2021) Assessing environmental impact reduction opportunities through life cycle assessment of apparel products. Sustain Prod Consum 28:663–674
107. Maraseni TN, Cockfield G, Maroulis J (2010) An assessment of greenhouse gas emissions: implications for the Australian cotton industry. J Agric Sci 148:501–510
108. Tan D, Brock PM, Hulugalle NR, Quigley G (2013) Life cycle assessment of cotton-corn farming systems in the Namoi Valley, Australia. In: Proceedings of the 8th life cycle conference (ALCAS), Manly. Citeseer
109. Ullah A, Perret SR, Gheewala SH, Soni P (2016) Eco-efficiency of cotton-cropping systems in Pakistan: an integrated approach of life cycle assessment and data envelopment analysis. J Clean Prod 134:623–632
110. Visser F, Dargusch P, Smith C, Grace PR (2015) Application of the crop carbon progress calculator in a 'farm to ship' cotton production case study in Australia. J Clean Prod 103:675–684
111. Fidan FŞ, Kızılkaya Aydoğan E, Uzal N (2022) The impact of organic cotton use and consumer habits in the sustainability of jean production using the LCA approach. Environ Sci Pollut Res 1–15
112. Thinkstep Sustainability Solutions (2019) Life cycle assessment of cotton cultivation systems better cotton, conventional cotton and organic cotton
113. Sphera (2021) Life cycle assessment of cotton made in Africa
114. Textile Exchange (2014) Life Cycle Assessment (LCA) of organic cotton-a global average
115. Doualle B, Medini K, Boucher X, Laforest V (2015) Investigating sustainability assessment methods of product-service systems. Procedia Cirp 30:161–166
116. Korpi E, Ala-Risku T (2008) Life cycle costing: a review of published case studies. Manag Audit J
117. Ciroth A, Franze J, Berlin G (2009) Life cycle costing in SimaPro. GreenDelta TC Berlin
118. Hall MR (2019) The sustainability price: expanding environmental life cycle costing to include the costs of poverty and climate change. Int J Life Cycle Assess 24:223–236
119. Aguilar Johansson I, Björkner M (2022) Social life cycle assessment of Denim fabric produced from Turkish Organic Cotton

120. Herrera Almanza AM, Corona B (2020) Using social life cycle assessment to analyze the contribution of products to the sustainable development goals: a case study in the textile sector. Int J Life Cycle Assess 25:1833–1845
121. Franco-García M-L, Haanstra W, Toxopeus M, Schuur B (2019) Social and environmental life cycle assessment (SELCA) method for sustainability analysis: the jeans global value Chain as a showcase. In: Towards zero waste. Springer, pp 215–237
122. van der Velden NM, Vogtländer JG (2017) Monetisation of external socio-economic costs of industrial production: a social-LCA-based case of clothing production. J Clean Prod 153:320–330
123. Zamani B, Sandin G, Svanström M, Peters GM (2018) Hotspot identification in the clothing industry using social life cycle assessment—opportunities and challenges of input-output modelling. Int J Life Cycle Assess 23:536–546
124. Ugaya CML, Brones F, Corrêa S (2011) S-LCA: preliminary results of Natura's cocoa soap bar. In: Proceedings of life cycle mangement conference
125. Naghshineh B, Lourenço F, Godina R, Jacinto C, Carvalho H (2020) A social life cycle assessment framework for additive manufacturing products. Appl Sci 10:4459
126. Bhanot N, Rao PV, Deshmukh SG (2015) Enablers and barriers of sustainable manufacturing: results from a survey of researchers and industry professionals. Procedia Cirp 29:562–567

The Environmental Impact of Textiles and Clothing: A Regional and a Country Approach

Marco Crestani, Laura Talens Peiró, and Susana Toboso Chavero

Abstract In the context of circularity, the European Commission has confirmed its intention to make sustainable textile products the norm in Europe as stated by the new EU Strategy for Sustainable and Circular Textiles. New Eco-design for sustainable products regulations will also be defined and become mandatory, including requirements for increased durability, reparability, recyclability, and recycled content. As part of the strategy, more support for research, innovation, and investments are denoted. However, understanding and advancing innovations for circularity in textiles rigorous data are needed to help account more accurately for the flows and stocks. Such accounting is key to support a more sustainable textile value chain and to define just textile waste reduction targets. This chapter proposes the Material Flow Analysis methodology as a powerful tool to shed light on the metabolism of textiles and clothing. It has also been proved useful to consider their related environmental impacts. To illustrate the use of the material flow analysis for the analysis of textiles, national scale (Spain), and regional scale (Catalonia) analyses are performed. The input data include yarn, fibres, and finished products. Current available statistical data on imports and exports confirm a notable growth in the flows of cotton, synthetic fibres, and both knitted and woven products. As a result, the textile waste generated by the high volume of consumption, along with the still low percentage of recycling and reusing approach, calls for further measures to minimise textile and clothing environmental impacts. Precise estimates of the flows of textile inputs and outputs in a geographical area along with their respective carbon footprint provide consistent results of their current environmental impact, key to better defining waste textiles prevention targets crucial to improve their sustainability.

Keywords Circular economy · Material Flow Analysis · Carbon footprint · Clothing textile impact · Textile waste · Fibres · Ecodesign

---

M. Crestani · L. Talens Peiró (✉) · S. Toboso Chavero
Sostenipra (2019SGR00734), Institut de Ciència i Tecnologia Ambientals (ICTA-UAB), Universitat Autònoma de Barcelona (Unitat Excelencia Maria de Maetzu MDM CEX2019-000940-M), 08193 Cerdanyola del Vallès, Barcelona, Spain
e-mail: laura.talens@uab.cat

S. S. Muthu (ed.), *Progress on Life Cycle Assessment in Textiles and Clothing*, Textile Science and Clothing Technology,
https://doi.org/10.1007/978-981-19-9634-4_8

1 Introduction

The global fashion industry has grown considerably since the early 2000s. Fashion brands are producing roughly double their production quantities today compared to the year 2000 [1]. By 2030, it is projected to increase from 62 million tonnes in 2015 to 102 million tonnes [2]. One of the main resulting effects is the large amount of non-renewable resources that are extracted to manufacture apparel and largely lost, after a short life period, in landfill or incinerated [3]. The main socio-ecological impact associated with the increase in textile production quantities is the large quantities of resources used for their production. Other factors contributing to their sociological effect are the low lifetime rate of textile utilisation, with limited reutilisation and recycling across the value chain [4]. However, while the increasing production per se has augmented the amount of textile waste generated, the change in textile materials used by manufacturers and designers in the production of apparel has led to a greater heterogeneous textile composition and thus makes the current treatment of textile waste even more complex [5].

The clothing textile system has become a high complex value chain where the different processes involved are spread across the globe. This globalised model started back in 1990 when the World Trade Organization applied market liberalisation and caused the strategic increase of imports for European consumption [6]. This also resulted in a significant reduction of the European textile production share. At present, raw materials for yarn and fibres are generally exported across countries to produce fabrics. Fabrics are in many cases exported as well to third countries to finally produce final apparel products, which are commercialised worldwide [7]. For example, the majority of textiles consumed by the European Union (EU) are manufactured outside the EU. In 2019, the main exporters of textile products to the EU were China, Bangladesh, and Turkey [8]. Addressing the whole clothing value chain is therefore challenging, especially because of its globally diverse structure and its marked power asymmetry between suppliers and global buyers, with a large number of small and medium-sized players involved at every level of the value chain [4].

In the EU, the textile clothing sector is economically significant but ecologically challenging often not putting quality, durability, and recyclability as priorities in the design and manufacturing of products [9]. The 2020 Circular Economy Action Plan [10] identified textiles for playing an important role in the circular economy transition. Clothing composes 81% of textile consumption in the EU, as a result the fashion sector was targeted as one of the key value chains in the plan [11]. However, before setting up measures and defining a strategy to improve the sustainability of the sector, it is important to make a diagnosis of the current state. To define guidelines and indicators, there is thus a need to establish a robust and a comprehensive methodology that could be taken as a benchmark for analysing all clothing flows in the EU. Enabling conditions for a wider uptake of sustainability and circularity in the textile value chain is an active area of research and can drive further innovation while advancing economies [11].

In Spain, apparel manufacturing is one of the largest industries, representing broadly 3% of GDP and guaranteeing high employability and strong international trade [12]. However, the life cycle of clothes in the country normally follows a linear model, where post-consumer textiles are sent up usually into uncollected disposal [13]. The resulting environmental concerns are augmenting and with the growth in textiles volume composed for most of the non-renewable inputs, the out-turns on water pollution and usage, energy expenditure, and carbon dioxide (CO_2) emissions. Moreover, as indicated by the Spanish Plan for Waste Management [14] only a small amount of textile clothing is collected separately, highlighting the still high rate of textiles not recycled. Domestic clothing waste is managed by agencies that are responsible for collecting and sorting waste by type and quality. In Spain, textile waste is classified as "specific collection" waste and must be deposit in municipal collection points [15]. A collection point is where communities can freely deposit their waste that cannot be disposed into unsorted waste [16]. They are managed by a specific non-profit organisation, which depends on the Autonomous Communities. In Spain, the most important are, Caritas and Humana [17]. Clothes can be reused when they are in perfect conditions, valorised when they have a different utility from what they were designed for, and in case they cannot be reused or recycled, they can be incinerated for energy recovery. As part of Spain, Catalonia has a share of 40% of the national textile economy and hires the 32% of Spanish employees in the sector. Considering that 50% of the textile material is used for manufacturing clothes, a high share of the revenues of the Spanish fashion sector are generated by Catalonia [18]. As for the general case of Spain, Catalonia holds a great percentage of non-recyclable or recycled items to produce clothing which, accompanied by an increasing household expenditure on clothing, leads to greater quantities of textile waste ending up incinerated or stocked in landfill [2].

In this context, the current research applies the Material Flow Analysis to study the flows of the textile sector in Spain and Catalonia, with a particular focus on the flows of cotton, wool, and other synthetic materials. The key goal is to get a better understanding of the importance of these flows and how they could be addressed with the objective to reduce their related environmental impacts. The results of this type of analysis would be valuable to assist the EC in implementing the EU Strategy for Sustainable Textiles. In April 2022, the EC indeed published its new EU strategy for Sustainable and Circular Textiles, sharing a novel circular vision with the objective to set new mandatory standards for more sustainable products. New products shall be designed to be more durable, reparable, and recycled [19]. By stating circularity as a priority, the EU pushes its member states to adopt progressively new legislation to improve the current textile business model.

This research covers the raw materials; the manufacturing of fibres, the spinning and transforming yarns into weaved or knitted fabrics, and the final clothing products [20]. The importance of mapping quantities composing the whole life cycle of clothing is relevant for understanding the current production, the consumption, and the waste paths. All this information is relevant in understanding the actions due to be implemented to improve the current state. The accounting of flows in mass units helps quantity the amount locally produced and compared it with the imports and exports flows. Accounting for the flows of each typology of materials as cotton, wool, and synthetic fibres provides a more detailed analysis at every stage of the life cycle. Section 2 provides a more detailed description of the fashion supply chain and processes forming Spanish and Catalan models. Section 3 summarises the approach taken to quantify the input and the output flows of textile clothes to a geographical system. An example of Catalonia and Spain are used to illustrate the use of material flow analysis. The description is useful to understand the data available on a national and a regional scale. Eventually, Sect. 4 reports the results of the textile flows at both levels. Based on these findings, the section discusses the potential environmental impacts of the textile value chain.

2 Overview: The Clothing Textile Industry in Spain and Catalonia

The activities related to a value chain are often shown as a linear representation from raw material to end-of-life treatment, with the potential for reuse or recycle adding loops to the linear clothing chain. For most garments, the production phase starts with fibre production, continues with the yarn construction, fabric manufacturing, and finishes with garment confectioning. The quantities and the materials of clothing textiles making up the Catalan and Spanish textile sector are multiple. The greatest share of materials includes synthetic, artificial, cotton, and wool [21]. Figure 1 illustrates the textile sector value chain as a linear representation of diverse processes from raw material to end-of-life treatment. When performing an MFA, as in this study, the inputs to the Catalan and Spanish textile value chain are generally a mix of fibres, yarns, fabrics, and finished clothes. Outputs are also generally a mix of diverse types of raw materials, semi-finished textile products, and finished textile products. Textile products can also be accumulated as a stock within a system. Therefore, the system does not include exclusively the flows from the domestic market, but also international trade flows which affect the local value chain. Thus, in an MFA, the domestic production of fibres, yarns, fabrics, and apparel clothing together with the imports as inputs needs to be balanced with the exports and the rest of textile products that are commercialised. Ultimately, used textile and post-consumer textiles are defined as well as part of the system. As illustrated by Fig. 1, the initial inputs in the value chain are fibres such as cotton, wool, and synthetic or artificial. As they are further processed, textile raw fibre inputs become progressively semi-finished products, which are in many cases further elaborated and mixed up leading to a great diversity of textile compositions difficult to distinguish in the final garments.

It is worth noting that textile products may also be imported or exported at each stage of the value chain. This adds more complexity to the analysis of the sector as it favours the "vertical disintegration and the global dispersion" of the processes ([22, p. 2). The following sections describe in detail each of the processes included in the value chain of textiles.

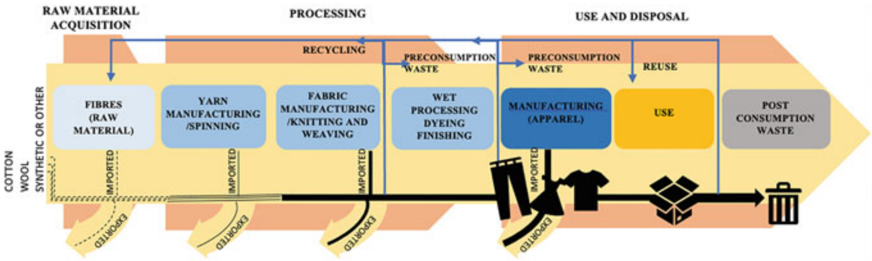


Fig. 1 General value chain of textile industry in Spain and Catalonia. The main yellow arrow illustrates the sequential processes included in the value chain of textiles and clothing. Arrows in black represent the export and import flows at each process. Blue arrows refer to the flows of fibres, fabrics, and clothing reused, recycled, and wasted along the value chain before becoming post-consumer textile waste

2.1 Fibres Production

The raw materials undergoing the first stage of the textile value chain are fibres. In a general view, a fibre is a small threadlike structure [23] composing the basic element of a textile, characterised by flexibility, fineness, and high ratio of length to thickness [24]. An industry definition says this is "a unit matter with a length at least 100 times its diameter, a structure of long chain molecules having a define preferred orientation, a diameter from 10 to 200 microns, and flexibility" ([25], p. 8). Based on their length fibres can be grouped in filaments (if of indefinite very great length) or staple fibres (if of much shorter length). To form yarns, filaments are normally combined and twisted, while staple fibres are spun [26]. Depending on their uses, they can be combined within the same fibre, or they can be blended with other types of fibres to enhance the quality of the end product [27]. In a nutshell, and according to the definition of Sinclair [26], fibres are the very foundation for all textile products. At this point, it is notable to consider the types of fibres in terms of materials used in the clothing textile industry, since part of the discourse of this study depends on it.

2.1.1 Fibres Composition

In general, fibres can be natural and man-made. Natural fibres are normally sourced by animals as wool or by vegetable as cotton. Natural fibres are cultivated or found in nature: cotton comes from the cotton seeds (*Gossypium Sp.*) and is almost composed by pure cellulose, with air and soft permeability, but there are also natural fibres originating from leaves (e.g. sisal) and stems (e.g. jute or hemp) [28]. Animal fibres are more properly known as protein-based fibres [28] for example wool, which comes from the shearing of sheep (*Ovis Aries*) and must be degreased and washed [29]. Man-made fibres are classified as synthetic and artificial [28]. Synthetic fibres are obtained by polymerisation of smaller molecules into larger ones (known as polymers) through

Table 1 Typologies of natural and man-made fibres. Own processing from [28, 31]

Natural fibres	Animal source	Wool
		Hair
		Silk
	Vegetal source	Seed (cotton)
		Bast (jute, hemp)
		Leaf (sisal)
Man-made fibres	Artificial source	Cellulose (rayon)
		Proteinic or regenerated (fibrolane)
	Synthetic source	Organic (acrylic, nylon, elastane, polyamide, polyester, polyethylene, polypropylene, polyurethane)
		Non-organic polymer (carbon, glass, metallic)

an industrial process. These polymers are later melted and poured through ditches in a spinneret, to result in a filament forming the fibres [30]. Eventually, artificial fibres refer to modified or transformed fibres chemically generated. Table 1 summarises diverse typologies of natural and man-made fibres.

This analysis will investigate the number of man-made and natural fibres flows. However, while man-made fibres will be evaluated as a unique flow, natural fibres will be accounted for as wool and cotton fibres, as suggested and developed already for the case of Catalonia in the work of [21].

2.2 *Yarns Manufacturing*

Yarn is an interlocked assembly of fibres twisted together to create a continuous strand suitable for the process of fabric manufacture [28]. The manufacturing processes for yarn vary depending on their origin, natural or man-made. Natural fibres are staple fibres by nature and are modified into yarns through a sequence of processes: opening, carding, combing drawing, roving, spinning, twisting, and winding [28]. Man-made fibres as synthetics fibres are instead used as filament yarns and twisted or sometimes texturised [20]. Yarns constitute a semi-finished product needed for the manufacturing of fabrics. As in the case of fibres, they can be locally manufactured or imported from other geographies. They can also be commercialised as a semi-finished products and thus exported from diverse countries.

2.3 Fabric Manufacturing

Fabrics are the main materials used in constructing cloth garments and textiles [32]. A fabric can be identified as a manufactured assembly of yarns that has considerable surface area in proportion to its thickness, and an adequate cohesion to permit the assembly to provide mechanical strength [24]. To produce fabrics, the yarn is either woven or knitted. During weaving two sets of yarns are interlaced to form the fabric at right angles to each other, while in knitting the loops are interlaced [33]. When creating the fabric, the type of loom is significant for the formation of the woven fabric, with the loom width determining the width of the cloth. Knitting can be done by hand or by special knitting machines. Alternatively to these two techniques, a nonwoven fabric can be produced directly from staple or filament fibres, with fibres bonded into fabrics by mechanical, chemical, or heat treatment [4].

2.4 Apparel Manufacturing

Once the fabric has been woven or knitted, a series of diverse processes are carried out to obtain the final apparel product. These processes aim to enhance the appearance, modify the weight or texture, or to improve the durability, flexibility, handling, or wase of care of the fabric [25]. Some of these processes may be adopted yet on the yarn before the weaving or knitted processes take place. The most common finishing processes are wet processes, bleaching, dyeing, finishing, and printing which eventually create the finished product. The decision of wet treatment is dependent on the material, the fabric chosen, and the design of the product [34]. Bleaching is usually adopted for light-coloured textiles and, sometimes, so it is for darker colours as pre-treatment before dying. Finished fabrics are printed in the confectioning, which also includes cutting, sewing, finishing, ironing, and packaging [20]. Figure 2 illustrates the inputs and the outputs of the textile sector in orange colour. The central part of the figure (blue colour) summarises the diverse processes included in the value chain explained in this section.

We consider within the system boundaries all the textiles used for clothing with a component of at least 80% of textile fibres [21]. Shoes and leather are excluded since they do not comply with the definition of clothing textile [21]. Home textiles like bedlinen, towels, tablecloths, curtains, upholstery textiles, carpets, duvets, and pillows are excluded from the analysis as well, as these are products where textile is not the dominant component. Besides, every industrial product is ruled out the system, being these products are not intended as clothing. However, we number clothing consumed by households and by government and business (e.g., general dresswear but also uniforms and workwear used by all public and private sectors, hotels, restaurants, and healthcare services). Another flow hard to track is pre-consumer textile waste. Pre-consumer textile waste refers to textiles generated within the production process that are not sold. Pre-consumer textile can also be referred as the by-product

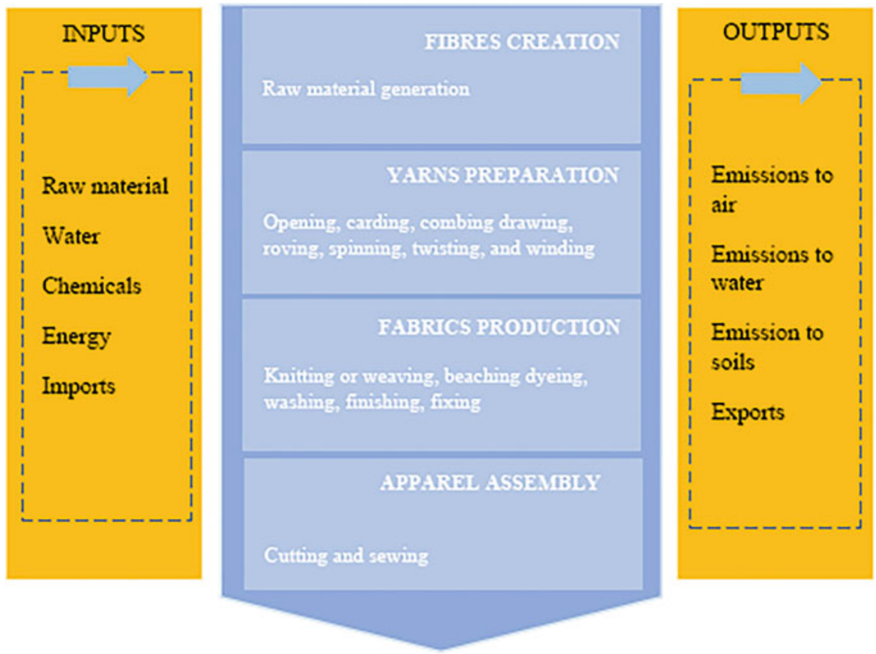


Fig. 2 Apparel manufacturing process in Spain and Catalonia

from spinning yarns, fibres, textile dyeing, and finishing process. Also, within this category are production surpluses or "deadstock". Both of these types of flows are not included in the scope of this work.

2.5 Post-consumer Textile

Post-consumer textile waste is defined as the textile products used by consumers which has lost its initial value and cannot continue to be used for the same purpose or because the consumer decides to get rid of it [6]. Textile waste can be discarded in the uncollected fraction of waste or can be separately collected in specific containers for reuse. At the textile collection facilities, items are classified for reuse and for recycling based on internal standard evaluation criteria. An item well-maintained that keeps its initial utility can be reused, while damaged or broken items are recycled. The recycling of damaged textile items recycled as other products as isolation material, rags, or as mattress stuffing is known as downcycling. According to the release on "good practices" issued by Datambient [29], due to the social tendency, the fashion standards, and consumption paths, the lifetime of clothing is shrinking gradually more, and consequently, the amount of textile waste is progressively increasing. Section 3 summarises the approach taken to quantify the main flows of textile to a geographical system as Spain and Catalonia: the domestic production, the imports and exports.

3 Materials and Methods

This part encloses a description of the methodology adopted to study the clothing sector in Spain and Catalonia in 2019. The method Material Flow Analysis (MFA) has been developed following Brunner and Rechberger [35]. It helps quantity a material *or* a product through the value chain and transformation processes included in the life cycle. MFA has been widely applied to study the patterns of material use and resource losses to the environment [36]. MFA is a systemic assessment based on the mass conservation principle used for evaluating the physical inputs and outputs from/to a system. The MFA approach fits within the Industrial Ecology systemic analysis, with Industrial Ecology defined as "the study of flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, regulatory and social factors on the flow, use and transformation of resources" [37]. In contrast to other tools describing material and energy systems, MFA uses system boundaries well-defined in space and time. For this reason, it helps to identify the accumulation and depletion of materials in natural and anthropogenic stocks, such as end products like clothes or soil and water, for a region or nation, both in our case and for a certain time [38]. In other terms, MFA permits to detect the shift of material stocks from natural reserves to anthropogenic accumulation, transforming different stock information into flow details characterising the system. As stated by [35] the objectives of MFA are:

- To create a system quantitatively representative of the considered metabolism, evaluating, in uniform terms, the relevant processes, materials, stocks, and constraining processes within clear boundaries.
- To consider the flows over time, controlling their trend and their possible evolutions.
- To minimise complexity while maintaining a robust basis.
- To apply a mass-balance approach for cross-comparisons and deficit checking.
- To serve as a benchmark for environment, resources and wastes assessment, and uncertainty analysis.

In general, MFA follows three main steps: the definition of the material and its system boundaries, the quantification of flows and stocks, and the interpretation of the results. The first step is to define the flow/stock under study and the description of the system and its scope, including time and space. The second step consists of the quantification of the inputs and outputs. In general, all the flows are expressed in mass units (i.e. kg or tonnes) but they can also be defined based on temporary boundaries (i.e. kg or tonnes per year). Once the quantification is concluded, the results are explained to evaluate and to identify potential improvements in the system.

In this MFA, the system to be analysed is the textile sector at two scales: regional (Catalonia) and country (Spain). The material flows include raw materials, i.e. fibres, semi-finished products such as yarns and fabrics, and final clothing as end products. In this MFA study, the clothing textile flows are classified according to (i) the total amount of textile product used for clothing, (ii) the textile typology employed for diverse items, and (iii) the quantities accumulated. Data obtained from the MFA is essential to account for the potential environmental impact of a system. In this case, the results of the MFA were combined with estimates of the carbon footprint of diverse textile products obtained by life cycle assessment (LCA) to account for the total carbon footprint of the textile sector.

3.1 Quantification of the Flows of Textiles

This section summarises the diverse approaches taken to quantify the main flows of textiles for a geographical system such as Catalonia and Spain. Quantities related to country production are balanced by imports and exports as in Fig. 3.

3.1.1 Domestic Production

Data of textile materials produced in Spain and Catalonia are available in the annual statistical Industrial Product Survey (IDS) conducted by the Catalan Institute for Statistics (IDESCAT, Annual Industrial Products Survey) and the Spanish Institute for Statistics [39]. In both cases, all quantities within the IDS are assumed to be declared as sold production. Information and data about the amount of textile and

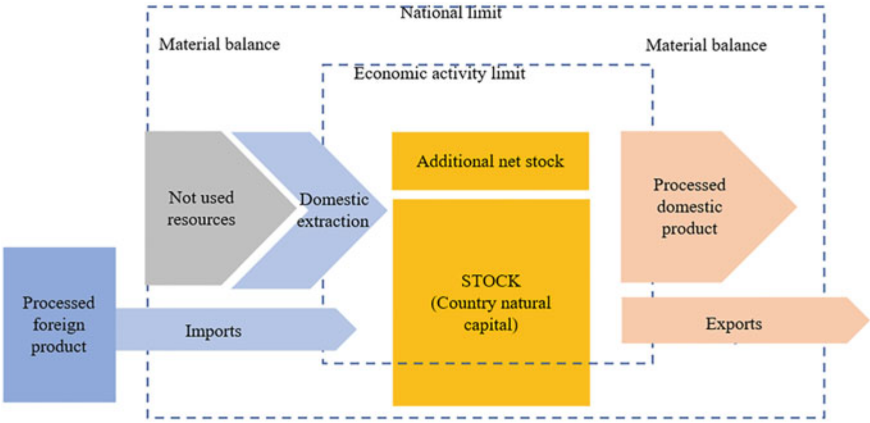


Fig. 3 Analysis of material flows for Spain and Catalonia

clothing discarded and stocked are however unclear. Data provided by both IDESCAT and INE are given using the National Classification of Economics Activities, CNAE-2009 [40]: this is a common methodology to define industrial products. Thus, the data provided are standardised and comparable to the rest of the EU member states. Data of the sold production are however defined using the PRODCOM code (INE, CNAE-2009) defined by the EU Statistical service Eurostat. The PRODCOM code consists of a series of numbers coinciding with categories of industrial products and services. According to the scope of this work, the selected PRODCOM code for the accounting are the codes 131 and 132 for dressmaking and textiles (yarns, fibre, and fabric), and the codes 139, 141, 142, and 143 for textile products and knitwear and garments other than knitwear. Data from the PRODCOM are expressed in diverse physical units as mass (tonnes), area (m^2), and units (u). The availability of data for the same material in diverse physical units represented one of the major difficulties encountered to develop a consistent MFA for the textile system in one single physical unit. In order to have all flows quantified in the same units, it was thus necessary to do some assumptions and use conversion factors. This was the case for fabrics and apparels, which were originally expressed in m^2 and units, respectively. Specific conversion factors to define a certain weight for m^2, and a defined mass per unit were used. To convert data of fabrics to mass (tonnes per year), an average density of 200 m^2/g as proposed by Nam Thai [41] was used. For apparel clothing, instead, conversion factors were needed to consolidate the primary data expressed in units, tonnes of units, pairs, and tonnes of grams. The quantities of panties and hosiery, gloves, mitts, and mittens were given as pairs. For panties and hosiery, only one unit was accounted for compared to gloves, mitts, and mittens, which generally refer to two units of the same product. The number of pairs was also converted from units to tonnes. All the quantities (in tonnes) for apparel items other than these were estimated by following the equation:

$$M_i(prod) = \frac{N_i}{12} * k_i * d_i \tag{1}$$

where M_i is the mass of apparel produced annually, N_i is the number of apparels produced yearly, k_i is actually the lengths in m^2 for designing the product, and d (g/m^2) is the density. N_i is divided by 12 since k_i is intended to be the length of 12 pieces of the product.

However, further assumptions for apparel conversion were needed, depending on the type of clothes and thus their respective mass. For instance, the density of a pair of trousers is greater than that of a pair of socks. Apparel products were thus classified into ten categories: t-shirt, shirt, trousers and short, jacket and short, dress, underwear, sportswear, children's clothes, *other*, and specific garments. *Others* included all other units of garments unclassified within the previous categories. Specific garments representing textile finished products for work (including clergy, professionals, dance, fencing, jockey, resistance for aviators, regional, costume, theatre, and bodysuits for external use) were already expressed in tonnes. Thus, their quantities were directly added to the final amount of textiles.

3.1.2 Imports and Exports of Textiles

Data on the trade of fibres and yarns were gathered from Datacomex [42], obtained directly from the Spanish government. Import and export quantities (in tonnes) are reported using TARIC codes instead of PRODCOM codes from the domestic production statistics database. The former integrates all measures relating to EU customs tariff, commercial, and agricultural legislation, while the latter attributes the number to its industrial category. As such, TARIC is a system used specially to monitor price harmonisation across the EU. For Catalonia, data were taken directly from IDESCAT, but TARIC numbers were the same as those for Spain (IDESCAT, foreign trade). Textile and textile-derived articles are displayed using the TARIC 50 to TARIC 63 codes. However, since we are investigating only textiles used for clothing, data for carpets and other textile floor coverings (TARIC code 57), textile articles of a kind suitable for industrial use (code 59), and other made-up textile articles and rags (code 63) were excluded. Data for other items than textiles, such as metallic and other materials under TARIC codes 56 and 58 were excluded as well. The complete list of textile materials and products accounted for in the MFA (including their PRODCOM and TARIC) is summarised in Fig. 4.

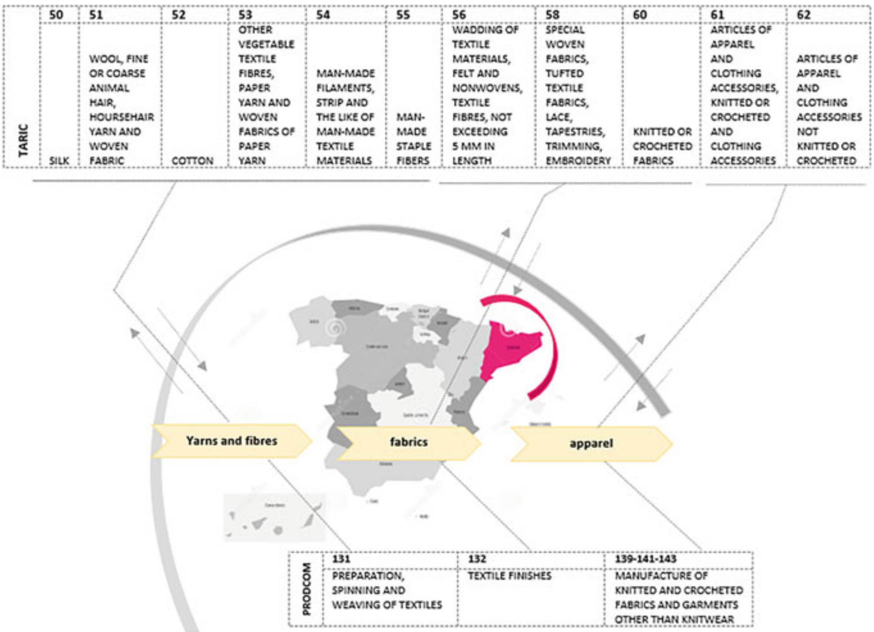


Fig. 4 Description of the PRODCOM and TARIC codes used to account for textile flows

3.1.3 Post-consumer Output

Data for the amount of post-consumer textile waste generated in Spain and Catalonia were taken from diverse sources. Details for Spain were based on MODAre- [6]: this novel study provides data gathered from different actors, such as agencies, Autonomous Communities, local institutions, and organisations managing the end of life for textile and clothing. Data is referred to represent 95% of the whole Spanish textile sector. Data for Catalonia were taken from yearly quantities given by the Catalan Waste Agency (Agència de Residus de Catalunya, ARC).

3.2 Environmental Impacts of Clothing Textile Sector

In order to measure the impacts generated by the fashion industry within the system, data from the study conducted by Niinimäki et al. [22] on energy use, freshwater consumption, and carbon dioxide (CO_2) emissions are used. The estimated figures for one kilogram of polyester, cotton, and wool are displayed in Fig. 5. These estimates are combined with the results of the MFA in order to get an educated guess of the environmental consequences of the natural and man-made fibre materials to use for clothing. Polyester is chosen as reference for man-made materials over, for instance, polyamide or polyethylene, since this former is the market leader in clothes manufacturing [43]. Polyester is indeed defined as the most widely used fibre in the world, accounting for roughly half of the overall fibre market and around 80% of synthetic fibres according to the Textile Exchange Preferred Fibres and Materials Report (2021).

4 Results

This section includes the number of raw materials (i.e. fibres and yarns) forming the input and generating the output (i.e., fabric, apparel, and waste) and reports the diverse typologies of textile materials alongside the stage of their life cycle stage for

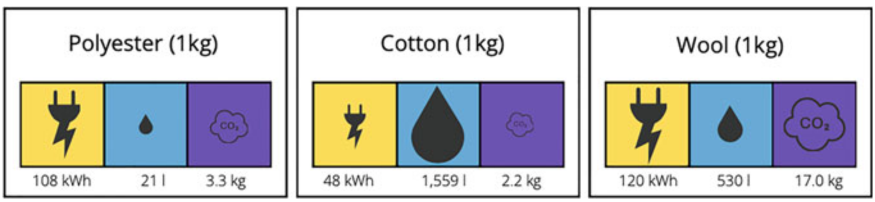


Fig. 5 Consumption of energy and freshwater, and carbon dioxide emissions for the production of one kg of polyester, cotton, and wool [22]

Spain and Catalonia. These amounts are further used to estimate the energy use, the water consumption, and the CO_2 emissions of the clothing sector. Lately, Sect. 4.3 introduces time-series considerations about clothing.

4.1 Results of the Textile Sector in Spain

To calculate the MFA at the scale of Spain, production, imports, and exports data relative to fibres, yarns, fabrics, and apparels were gathered. In 2019, the production of fibres, yarns, and fabrics was estimated to be 65,185 tonnes, 136,828 tonnes, and 107,993 tonnes, respectively. Table 2 shows the total amount of apparel produced in 2019. Their quantities are given for ten different typologies as described in Sect. 3.1.1. As total, Spain produced 71,749 tonnes of apparel items.

When all categories are considered, production quantities can be estimated according to the material used: *cotton, synthetic or artificial*, and *wool*. *Cotton* constitutes more than 40% of the total share of raw materials produced in 2019 but represents less than 10% of fabrics and apparel produced for the same year. *Synthetic or artificial* amount to around 50% of raw materials produced and almost 90% with respect to the production of fabric and apparel. *Wool* has a limited presence, with the highest reached in fibres with 8% (Table 3).

As shown in Fig. 6, the inputs to the fibres and to the yarns stages of the value chain are half composed by natural material and half by man-made. However, this share changes at the fabric and apparel stage, the latter processes of the textile value chain, almost entirely made of synthetic or artificial materials.

Imported fibres, yarns, farbics, and garments were also classified considering their material composition. The total amount of textile for clothing imported accounted

Table 2 Amount of clothes produced in Spain in 2019

Items	Quantity (10^6)	m^2/pieces	Length (m^2)	ρ (g/m^2)	Mass (tonnes)
T-shirt	32.4	18.4	49.7	121.9	6,062
Shirt	50.7	20.1	84.8	125	10,605
Trousers & Short	47.7	14.9	59.3	200	11,854
Jacket & Short	23.8	34.5	68.3	244.8	16,721
Dress	35.7	14.9	44.4	130	5,771
Underwear	99.0	9.2	75.9	83	6,300
Sportswear	20.0	12.5	20.8	150	3,119
Children clothes	0.8	9.3	0.6	159	93
Others	82.4	12.5	85.8	130	11,160
Specific garments	–	–	–	–	64
Total	392.5	146.3	489.7	1,343.7	**71,749**

Table 3 Estimated quantities of production of fibres, yarns, fabric, and apparel fibres for cotton, synthetic and artificial, and wool for Spain in 2019

Production per typology of materials	Fibres		Yarns		Fabric		Apparel	
	Tonnes	%	Tonnes	%	Tonnes	%	Tonnes	%
Cotton	28,170	43	63,124	46	9,938	9	6,752	10
Synthetic and artificial	31,664	49	69,955	51	97,619	90	63,512	88
Wool	5,351	8	3,749	3	435	1	1,485	2
Total	65,185	100	136,828	100	107,993	100	71,749	100

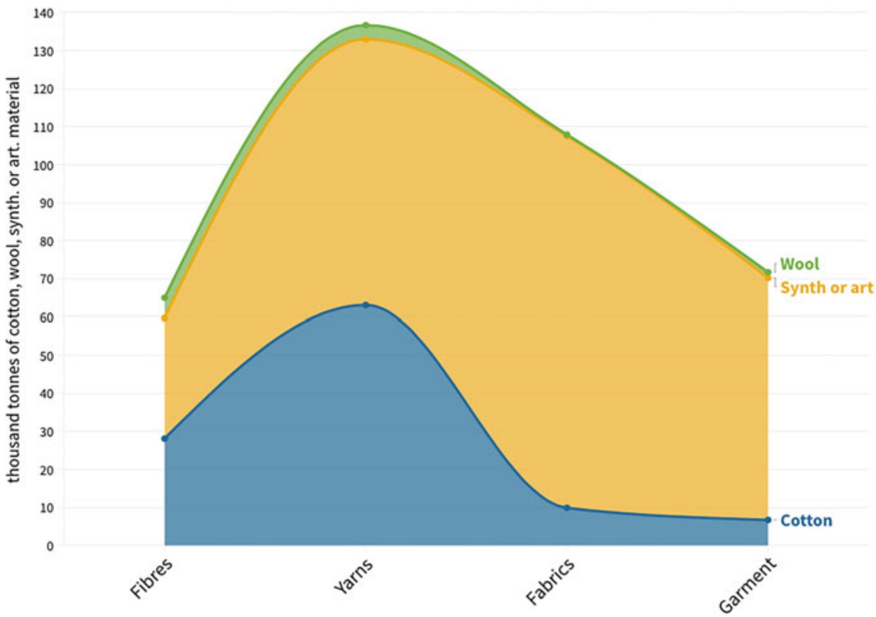


Fig. 6 Estimated quantities (all in thousand tonnes) of materials used by the Spanish textile sector. Cotton (blue), synthetic and artificial (yellow), and wool (green)

for 1.6 million tonnes. The majority of imports were apparel items with more than 1 million tonnes. The results shown in Fig. 5 illustrate how *synthetic or artificial* materials dominate the trade at every level of the textile value chain. However, it is worth noting that the amount of *cotton* increases progressively along the value chain, from 4.5% share of the whole imports of fibres to 44.4% in imported apparel. Comparably, the level of *synthetics or artificial* almost completely forms the imported inputs, suggesting the almost totality of imported inputs for Spain are man-made fibres. The imported raw materials are for 94.5% of synthetic or artificial and 4.5% of cotton, the further in the chain and in the production chain, the least the gap. Apparels,

Table 4 Estimated imports of fibres, yarns, fabrics, and apparel fibres for cotton, synthetic and artificial, and wool materials for Spain in 2019

Imports per typology of materials	Fibres		Yarns		Fabrics		Apparel	
	Tonnes	%	Tonnes	%	Tonnes	%	Tonnes	%
Cotton	10,608	5	35,780	19	41,112	22	448,754	44
Synthetic or artificial	224,084	94	150,809	80	141,196	76	550,190	55
Wool	2,422	1	2,102	1	3,492	2	11,172	1
Total	237,114	100	188,690	100	185,800	100	1,010,116	100

which in our system represents part of the output, are, respectively, composed of 44.4% of *cotton* and 54.5% of *synthetic or artificial as shown in* Table 4.

In 2019, the total amount of textiles for clothing exported was 979,259 tonnes. In all categories the quantities of export were lower when compared to import quantities. The greatest flow of exports was apparel, representing 54% of all textile products exported. Fibres, yarns, and fabrics range from 12 to 19% of the total exports. In terms of material, *cotton* is the greatest fibre exported, constituting two-thirds of the whole external supply. This proportion decreases severely for exported yarns and fabrics. The share of cotton varies similarly for imports. *Synthetics or artificial* fibres represent only 24.7% of the whole exported fibres. However, they represent more than half of yarns and fabrics exported and 52.6% of apparels exported. While wool amounted to around 1–2% for all categories in imports, this is only true for exported fabrics and apparels. Wool has the lowest percentage, representing the 8% of exported fibres, and less than 5% for the rest of the typologies disclosed in Table 5.

For clothing textile waste, data are based on the research proposed by MODAre-[6] which attributes an average of 890,000 tonnes of generated waste to Spain in 2019. The average amount of textile waste generated per citizen per year was estimated to be 2.3 kg. From the entire textile waste amount, about 108,296 tonnes are collected separately in specific containers, which represents about 12% of the total textile

Table 5 Estimated exports of fibres, yarns, fabrics, and apparel fibres for cotton, synthetic and artificial, and wool materials for Spain in 2019

Exports per typology of materials	Fibres		Yarns		Fabrics		Apparel	
	Tonnes	%	Tonnes	%	Tonnes	%	Tonnes	%
Cotton	98,192	67	34,612	30	41,965	22	244,553	46
Synthetic or artificial	36,126	25	75,773	67	141,474	76	279,945	53
Wool	11,711	8	3,439	3	3,598	2	7,872	1
Total	146,029	100	113,824	100	187,036	100	532,370	100

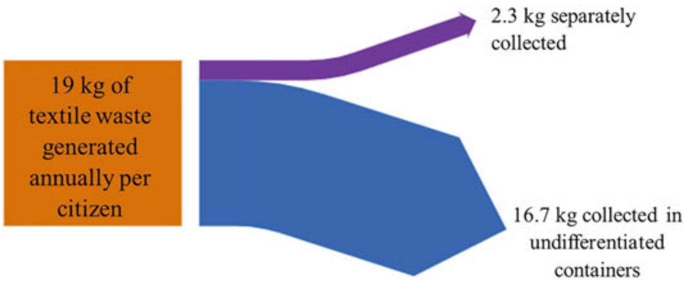


Fig. 7 Annual amount (in kg) of textile waste generated per citizen in Spain in 2019

waste. This fact suggests that in Spain each citizen consumes every year 19 kg of textile or clothing products separating only the 12% [21] as synthetised by Fig. 7.

Using data for production, trade, and waste, Fig. 8 illustrates the input and the output flows of the Spanish textile sector for 2019. On the one hand, the production of textile products represents about 20% of the total inputs demonstrating that the Spanish textile sector depends strongly in the import from third countries. On the other hand, almost 50% of the imported textiles are later on exported to third countries, also illustrating that Spain has important textile exporters companies. As shown in previous data, the amount of textile waste collected separately for reuse and recycling is negligible when compared to the quantities of textiles disposed of in unsorted containers.

Based on the estimates given in Figs. 6 and 8, the consumption of water and energy as well as the related CO_2 emissions generated by the textile system in Spain can be calculated. The potential environmental impact of textile production was calculated assuming that yarns, fabrics, and apparel products generate at least the same environmental impact than fibres, as the starting point of all these semi-finished products are fibres. Figure 9 shows that the current textile sector in Spain consumes 178×10^6 MWh of energy and over one thousand million tonnes of water. It also generates 6.3 million tonnes of CO_2 emissions. Most of these impacts are produced locally in the production sites and are not considered a direct impact of the textile sector in Spain. From a material perspective, cotton generates over 95% of the total water consumption while polyester consumes about 80% of the total energy

Fig. 8 Input and output flows (in thousand tonnes) of the Spanish textile sector in 2019

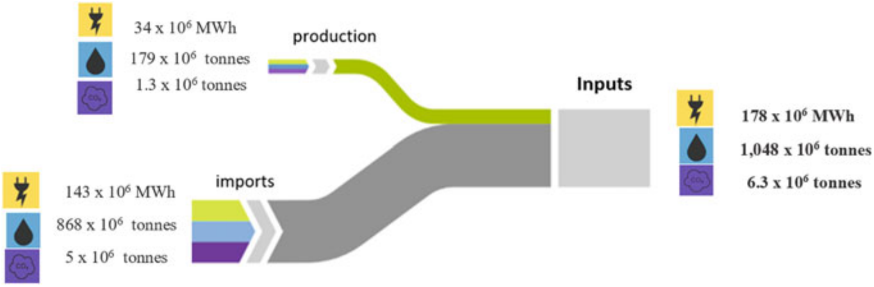


Fig. 9 Estimated energy and water consumption, and CO_2 emissions of the total natural and man-made textiles for clothes in Spain in 2019

consumed by the sector and generates about 70% of the total CO_2 emissions. The results of the MFA performed combined with the estimates of the environmental impact of the diverse typologies of materials provide a powerful information that helps understand the environmental impact of both the domestic production and imports. This information is highly relevant to define the most effective way to improve the sustainability of the textile sector.

4.2 Results of the Textile Sector in Catalonia

Analogously to the analysis of the Spanish textile sector, the Catalan production, import and export flows were analysed. Obtaining further information at Catalan level is significant since Catalonia presents a high share of the fashion industry in Spain. The last release of INE about Industrial production confirms that Catalonia has the highest national sold textile production in years [39]. Additionally, conducting an MFA at the regional level can support local strategies while evaluating and developing policy decisions and guiding tools. A regional MFA approach was, for instance, already presented by Hendriks et al. [44] in their study of resource and environmental management for the city of Vienna and the Swiss lowland. The authors were retaining this regional approach as highly potential for forming part of a regional environmental management and audit system. As such, here below the results for Catalonia are presented. Table 6 shows the amount of clothes produced in Catalonia in 2019. As already explained earlier, in some cases the quantities were given in diverse physical units and conversion factors were needed in order to obtain the total amount of inputs and outputs in the same units.

In the total amount of clothes produced in Catalonia, t-shirt manufacturing accounts for 4,211 tonnes representing the 19% of the whole garments production. The lowest data registered are specific garments and children's clothes, in line with Spain as reported in Table 1. Relatively to materials, we cannot discourse on fibres, although we observe yarns are mostly composed by cotton, with around 58% of cotton

Table 6 Amount of clothes produced in Catalonia in 2019

Items	Quantity (10^6)	m^2/pieces	Length (m^2)	ρ (g/m^2)	Mass (Tonnes)
T-shirt	22.53	18.4	34.5	121.9	4,211
Shirt	10.60	20.1	17.8	125	2,220
Trousers and short	11.18	14.9	13.9	200	2,777
Jacket and short	4.39	34.5	12.6	244.8	3,092
Dress	17.90	14.9	22.2	130	2,889
Underwear	42.11	9.2	32.3	83	2,679
Sportswear	13.13	12.5	13.7	150	2,052
Children clothes	0.06	9.3	0.0	159	8
Others	14.36	12.5	15.0	130	1,945
Specific garments	–	–	–	–	51
Total	136.3	16.3	18.0	149.3	**21,923**

yarns produced. However, as we move alongside the value chain (as described in Fig. 1), a shift from *cotton* production to *synthetic or artificial* materials is observed. This is also observed in Table 7 where both present the 96.1% in the production of fabrics and the 93.2% in apparels. There is no indication about fibres production in Catalonia in 2019, so the amount is assumed negligible. The production of yarns and fabrics is of 81,506 and 57,456 tonnes, respectively. For apparels, the total amount of clothes is estimated to be 21,923 tonnes. These results are consistent with those already given for Spain: *synthetic or artificial* occupy almost equally inputs production, but their share is almost entirely composed the structure of fabrics and apparel (also illustrated in Fig. 10).

The amount of imported textile for clothing and clothes amounts to 601,867 tonnes, as given in Table 8. Most imports are due to the procurement of apparels, which composes more than 50% of all replenishment. The least imported good is fabrics with about 10%. Regarding the material composition of these flows, as data of Catalonia do not provide accurate information about it, it is assumed that the share of

Table 7 Estimated quantities of production of fibres, yarns, fabric, and apparel fibres for cotton, synthetic and artificial, and wool for Catalonia in 2019

Production per typology of materials	Fibres		Yarns		Fabrics		Apparel	
	Tonnes	%	Tonnes	%	Tonnes	%	Tonnes	%
Cotton	–	–	47,326	58	2,077	4	1,283	6
Synthetic or artificial	–	–	32,953	40	55,193	96	20,435	93
Wool	–	–	1,227	2	186	0	205	1
Total	–	–	81,506	100	57,456	100	21,923	100

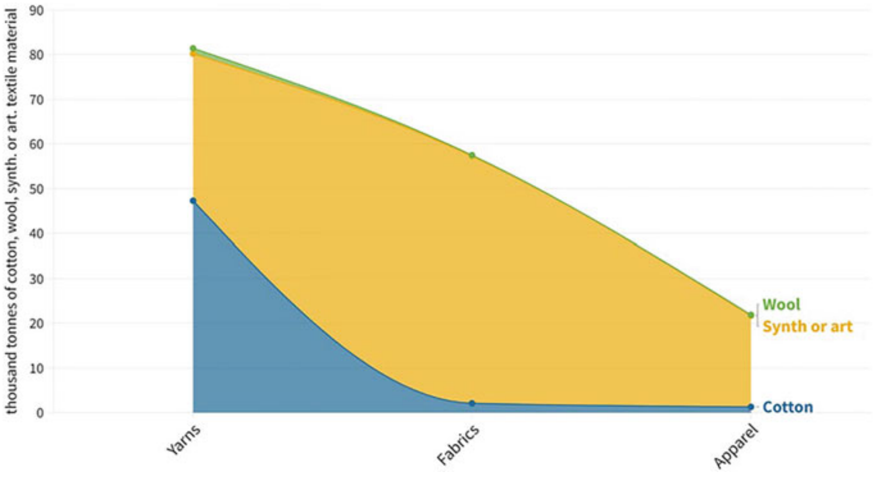


Fig. 10 Estimated quantities (all in thousand tonnes) of materials used by the Catalan textile sector. Cotton (blue), synthetic and artificial (yellow), and wool (green)

the type of materials for Catalonia is like that of Spain. Based on this assumption, the amount of cotton increases along the value chain. The quantity changes from 4.5% for fibres to 44% in apparels, with progressive increase from fibres to apparels. The amount of synthetic or artificial materials however evolved in the opposite manner. The share of wool is up to 2%, but stable along the production.

In Catalonia, 299,139 tonnes of textiles used for clothing and clothes were exported in 2019. The greatest part was the supply of apparel, with 168,809 tonnes of clothes shipped, while fibres amounted for the lowest with 11,289 tonnes. Fibres exports supplied consisted of 75% of cotton and 25% of synthetic or artificial materials. Yarns are meanwhile distributed for 2/3 of *synthetic or artificial* and for 30.4% of *cotton*. For fabrics, the percentage of *synthetic or artificial* increases to its peak, reaching the 76%. Eventually, *cotton* and *synthetic or artificial* form apparel exports

Table 8 Estimated imports of fibres, yarns, fabrics, and apparel fibres for cotton, synthetic and artificial, and wool materials for Catalonia in 2019

Imports per typology of materials	Fibres		Yarns		Fabrics		Apparel	
	Tonnes	%	Tonnes	%	Tonnes	%	Tonnes	%
Cotton	5,322	5	19,391	19	13,081	22	142,844	44
Synthetic or artificial	112,418	94	81,731	80	44,926	76	175,132	55
Wool	1,215	1	1,139	1	1,111	2	3,556	1
Total	118,955	100	102,261	100	59,119	100	321,532	100

Table 9 Estimated exports of fibres, yarns, fabrics, and apparel fibres for cotton, synthetic and artificial, and wool materials for Catalonia in 2019

Exports per typology of materials	Fibres		Yarns		Fabrics		Apparel	
	Tonnes	%	Tonnes	%	Tonnes	%	Tonnes	%
Cotton	7,591	67	21,656	30	10,730	22	77,545	46
Synthetic or artificial	2,793	25	47,410	67	36,173	76	88,768	53
Wool	905	8	2,152	3	920	2	2,496	1
Total	11,289	100	71,218	100	47,823	100	168,809	100

for, respectively, the 46 and 53%. Wool has its maximum percentage of exported fibres and reduces gradually to apparels (Table 9).

According to MODAre- [6], the annual textile waste generated per citizen for Spain and Catalonia is the same (19 kg). This is probably because it is generally calculated using data at country level without considering any possible differences between regions. As result, the average textile waste generated per person remains unaltered. A study conducted by the Institutional system of Catalonia (2020) says that each Catalan generates 21.6 kg of textile waste each year. In this study, data from Catalonia was preferred over data from Spain. Thus, the amount of textile waste estimated equals 165,933 tonnes per year as reported by the Catalan Waste Agency [45]. For the 2019, data shows that from a total of 18,521 tonnes of textile waste, only 11% was collected separately while 89% ended up in the undifferentiated waste fraction, as shown in Fig. 11.

Figure 12 shows the flow of textiles to and from Catalonia in 2019. The domestic production represents about 20% of the total input flows. The export of textile is almost 40% of the total input flows to Catalonia. In line with the results from Spain, the quantity of textile waste separately collected is low. In Catalonia it represents about 4% of the total output. The amount of textile waste unsorted remains high, it is over 30%.

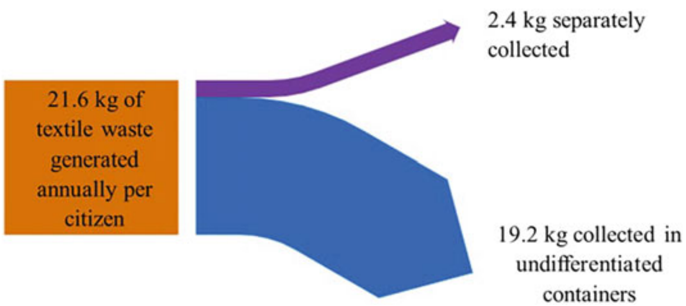


Fig. 11 Annual amount (in kg) of textile waste generated per citizen in Catalonia in 2019

Fig. 12 Input and output flows (in thousand tonnes) of the Catalan textile sector in 2019

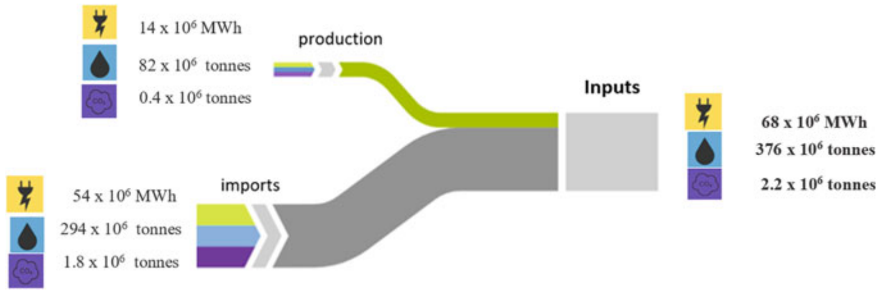


Fig. 13 Estimated energy and water consumption, and CO_2 emissions of the total natural and man-made textiles for clothes in Catalonia in 2019

Analogously as done for case study of Spain, the potential impact of the textile sector in Catalonia can be calculated by using data on energy and water consumption, and the CO_2 emissions shown in Fig. 5. Figure 13 shows the results from these three variables for the total of 763 thousand tonnes of imported and domestically produced textiles for clothing. The 95% of water consumption is due to cotton, while polyester is responsible for the 82% of energy use and the 72% of CO_2 emissions.

4.3 Trends and Paradigms of the Textile Sector in Spain and Catalonia

When evaluating the domestic production of clothing textile from 2016 to 2020, the trend for Spain reaches its production peak in 2018 with 388,981 tonnes produced. In 2020, a reduction in production was shown (see Table 10). This might be explained by the drop in turnover and the decreasing in spending during pandemic [46] along with the significant impact of COVID-19 on this labour-intensive and highly globalised industry [47]. The number of fibres, yarns, and fabrics decreased by 10% approximately from 2019 to 2020. Apparel experienced the highest decrease, reducing by 17% from 2019 to 2020. This data describes coherently the challenges faced starting in 2020 by the fashion and apparel industry, which had to deal with budget cuts and orders cancellation due also in part to spin-off effects of social distancing measures [48].

Table 10 shows the percentages of materials in production and imports from 2016 to 2020 in Spain. As observed, *synthetic or artificial* has increased, while cotton has slightly decreased and wool has an constant rate. Together with production, also imports show the same material composition trend for these years. Data from imports and production confirm *synthethic or artificial* compose most part of the clothing textile and are in accordance with statements reporting the presence on the market of approximately 60% of *synthetic or artidicial* fibres with respect to other materials [7].

However, when evaluating both imports and exports, we observe they were experimenting with an upward evolution before the year 2020 (Table 10) when they drastically decreased compared to figures before the pandemic. Hence, not accounting for the pandemic effect on the trend, a steady production, together with an augmenting trade, outlines the European ambition to increase the global market share of the textile industry, also called nearsharing [49], and confirms the extremely globalised supply chain of the clothing business [7].

Analogously to Spain, Catalonia experimented a similar production trend, with *synthetic or artificial* forming more than 60% of the domestic production as shown in Table 11.

We cannot argue the material composition of trade for Catalonia, since there is no record reporting this information and we assume broadly the same proportions as those for Spain. However, we noticed that there is a great amount of apparel imported

Table 10 Tonnes and percentage of materials in textiles from 2016 to 2020 in Spain

Materials in textiles	2016	2017	2018	2019	2020
Production (all in %)					
Cotton	31.0	31.8	30.4	28.3	28.9
Synthetic or artificial	66.2	65.7	66.9	68.8	68.7
Wool	2.8	2.5	2.7	2.9	2.4
Imports (all in %)					
Cotton	33.7	34.7	33.6	33.1	32.2
Synthetic or artificial	64.9	64.0	65.2	65.7	66.7
Wool	1.4	1.3	1.3	1.2	1.1

Table 11 Tonnes and percentage of materials in textiles from 2016 to 2020 in Catalonia

Materials in textiles	2016	2017	2018	2019	2020
Production (all in %)					
Cotton	31.3	31.2	30.5	31.5	32.5
Synthetic or artificial	68.5	68.5	68.6	67.5	66.6
Wool	0.1	0.2	0.8	1.0	0.9

Table 12 Trade of clothing textiles per product type from 2016 to 2020 in Catalonia

Tonnes of imports and exports	2016	2017	2018	2019	2020
Imports (in tonnes)	**560,839**	**595,715**	**605,451**	**601,867**	**503,181**
Fibres	109,385	106,271	114,225	118,955	110,185
Yarns	122,338	119,788	115,137	102,261	88,934
Fabrics	59,097	62,099	59,892	59,119	40,057
Apparel	270,019	307,557	316,197	321,532	264,005
Exports (in tonnes)	**238,492**	**287,679**	**289,477**	**299,139**	**253,301**
Fibres	9,773	11,103	11,055	11,289	7,930
Yarns	77,637	84,767	73,970	71,217	60,746
Fabrics	52,337	53,387	49,244	47,823	38,763
Apparel	98,744	138,423	155,208	168,809	145,863

with respect to other products along the value chain; this kind of result was already shared by the European Environment Agency at the Union level [7]. The present study confirms a similar effect as well at Catalan and Spanish level (Table 12).

Furthermore, when we compare the trades of Catalonia over Spain from 2016 to 2020, we observe that on average imports to Catalonia represent from 37 to 39% of the total Spanish textile imports. However, the exports in Catalonia represent from 28 to 32% of the total exports in Spain. Given the increase in exports, except for 2020, Catalonia is indeed more and more part of the global selling, increasing from 28% in 2016 to 32% over Spain in 2020 and establishing its role not limited to the national economy but also within the global scenario [21].

5 Discussion

In the light of the results above, it is useful to further discuss the socio-environmental impacts of the fashion sector based on the accounting performed, and also on the existing barriers to implement a more sustainable fashion industry.

5.1 The Socio-environmental Cost of Fashion Industry

Recently, the fashion industry has been blamed for not considering the social and environmental impacts as part of its cost-analysis agenda [22], with major concerns intrinsically rooted into the "vertical disintegration and global dispersion" defining the supply chain model of fashion businesses [50]. Hence, the first analysis must be advanced within the life cycle of each garment. The global production of textiles used for clothing, from fibres to garment, spans several manufacturing, logistics, and retail industries, apart for agricultural and petrochemical work, for cropping and fibres creation. The decentralisation towards lower-labour-cost countries has generated the decline of production in many developed countries and the increase of the supply chain complexity up to the point in which it might be difficult for downstream manufacturers to know transparently the origins of raw materials and the way in which they were processed [51]. The production of apparel, including the processes to transform fibres to yarns, then to fabrics, and later to apparel, often occurs in different countries leading to an increase in the steps between processes and complicating the logistics aspects [5]. This effect is also somehow observed in the case of Spain and Catalonia. For Spain, the domestic production represents only 24% of the total imported textiles. The greatest import quantities occur at the end of the value chain where inputs are finished apparel (Table 5). It is also observed that the amount of the imports of materials increases along the value chain, particularly for synthetic and artificial materials. For Catalonia, the domestic production is slightly higher than Spain (almost 27%) of the imports of textiles. However, it is worth to mention the trend of synthetic and artificial materials whose quantities do not follow an increasing trend along the value chain. For example, the amount of imported fibres to process is very close to that at the apparel manufacturing. In parallel with social costs, at each stage of the supply chain, the fashion industry generates environmental impacts due to the use of materials and energy inputs during the life cycle of textiles and apparel clothing. Figures 9 and 13 show an educated guess of the quantity of water and energy, as well as the CO_2 emissions derived from the amount of apparel clothes consumed in Spain and Catalonia, respectively. In Spain, the apparel sector is responsible for the consumption of 1 billion tonnes of water and almost 2 TWh of electricity. It also generates over 6 million tonnes of CO_2 emissions. Catalonia represents over 35% of the total consumptions and the CO_2 emissions of the quantities for Spain.

For example, the fashion business uses an estimated average of 1,559 L of water for the manufacturing of *one* kilogram of cotton fibre (Fig. 5), considering that most of the usage is due to cotton cultivation and wet processing of textile manufacturing [22, 22]. Indeed, cotton is reported to be the most water-intensive material of any fashion fibre. A high demand of water for textile production might turn into an Environmental Justice problem, when most parts of its socio-ecological effects occur in places other than where the item is consumed. At European level, for instance, it was estimated that 20% of the water suffered by the Aral Sea was because of the cotton consumption within the EU [52]. Moreover, with water scarcity also water safety might impact on local water supplies by improperly releasing chemicals into local groundwater, with the risk of degradation for the whole ecosystem and with impacts spread unevenly amongst communities [5]. As a matter of fact, chemical pollution is greatest where cotton is cultivated and in regions where water used in the production phase is not well-purified. Nevertheless, evaluating the GHGs emitted per kg of fibres, the highest carbon footprint comes from fossil products production, such as polyester [53], for Spain and Catalonia synthetic or artificial items produced indeed have the highest impact in CO_2 with respect to other materials. This negative effect might depend on the sole high energy demanded but also on the source of energy used [53]. In the case of China, for instance, the carbon footprint for textile manufacturing is larger than textiles made in Turkey and in Europe, given its high share of coal in the energy system [20, 53]. Although synthetic extraction and processing might drive high carbon footprint, adopting other perspectives, cotton cultivation also demands a great number of agrochemicals, which in turn leach into the soil, and can cause human and environmental impacts [54]. Connected to the risk of what crop technique and in what quantity has been used, there is also the issue with what type of information has been shared alongside the disintegrated chain: when, for example, EU decides to import semi-finished goods from outside of the EU, the limited data on material safety increases the environmental risks from unsafe usage or disposal [55]. In this complex game of incomplete information and numbers, the environmental burdens rise and are, anyhow, disproportionately distributed between the Global North and the Global South communities [56]. Thus, along with effects quantification, the fashion supply model should also evaluate a discourse assessment able to gather qualitative aspects. As a matter of fact, discussing the Social and Environmental injustice created is key to understand the disproportionate global impacts experienced by the global consumers and the global producers and might be considered as a discourse ground in which a broader and inclusive technical evaluation of life cycle of cotton and synthetics should operate [57].

5.2 Existing Barriers to Reduce Textile Waste

So far, we debated a lot on the impacts exclusively related to inputs of the system. As a matter of fact, we did not consider what and if the output of the system might produce or reduce some impacts. While exports are ruled out since part of other national or local accounting (see Fig. 3), we can instead discourse further on the opportunity cost of not choosing disposal methods different than landfill, which is the actual major end-of-life option in the business as usual. When reuse is applied, we can suggest that a consumer instead of buying a new-brand cloth decides to buy reused. If this is the case, all the costs that would have been associated to generate new clothes are negligible. Recycled polyester and cotton have been calculated to use only 1.8 and 2.6% of the necessary energy to process virgin fibres [58], while the CO_2 saving is mainly due to oil extraction avoidance. In some situations, however, textile incineration could be more sustainable with respect to recycling, if considering energy recovery, as there might be chemicals that are not recyclable or recycling [59]. Hence, in light of today available waste treatments, it would be significant for future analysis, and it represented an assessment limitation for this paper, to calculate the saved impacts from choosing a more circular economy model and to include it into impacts application to MFA. The above call for including also saved effects in the impact assessment for textile sees in the EU regulatory panorama its first motivation, being the transition towards a circular economic model a policy priority for the European Commission [11]. In the EU vision, textiles and clothing textiles placed on the market should be designed to be more durable, with their lifetime prolonged through repair and transfer to new users, in order to extent the active use such that in the end of life the materials would be possible to recycle into another high-quality item. In March 2022, the EU commission laid out new key principles and actions to take for driving this change within the Union, sharing the importance to move away from a business model which has the fourth highest impact on the environment and climate change, the third for use of water and land and the fifth for primary raw materials usage and GHGs emissions [19]. As part of the strategy, actions must be taken alongside the entire lifecycle of textiles products, addressing the textiles design and the way they are consumed in order to improve products' environmental performance. This includes dealing with textile products' material composition, the fibres adopted and their blending, and the content of chemicals of concern that limit the recycling at their end of life.

As shown in the results of Sect. 4, even though the share of cotton represented the greatest amount of imported fibres in 2019, data showed that the share of synthetic and artificial materials gained much more importance in later life cycle stages. For instance, these fibres include a synthetic fibre as elastane which is added to enhance the functionality of textiles. Their use however can negatively impact the economical convenience and the environmental cost of the recycling of textiles made of these fibres [60]. Moreover, for thermo-mechanical recycling, blending different types of polyester can also complicate the processing of textiles waste and the efficiency of recycling [19]. Therefore, estimating the total share of these typologies of fibres can turned into a prevention action to avoid certain problems in the recycling of textile waste. Indeed, the EC is presently discussing on the introduction of mandatory Eco-design requirements to build product-specific eco-standards which could improve the recycling, and thus the sustainability textiles. In general, the strategy will leverage on supporting new manufacturing procedures, incentivising recycling and restricting waste disposal, but also on changing consumption paths, encouraging a shift towards quality and durability, in order to address both the supply and the demand challenges the whole business creates.

From January 2025, the separate collection of domestic textile waste will be mandatory in all member states of the EU [15]. As response to the Spanish law 22/2011 and the directive 2008/98/C, Spain has implemented the Country Plan for Waste management in order to improve domestic waste management and commercial waste not attributing to industrial use [14]. The main aim is to improve domestic waste separation, collecting aggregation, and associates' agreements [6]. This new Spanish Waste Law establishes that by 2025 at least 55% of household waste, including textiles, should be prepared for reuse or destined for recycling. This percentage is set to rise to 60% in 2030 and 65% in 2035. Catalonia also adopted the General Programme of Prevention and management of Waste and Resources of Catalunya (PRECAT) which includes the prevention and management of municipal textile waste [61]. In addition, the Catalan Minister of Climate Action, Food and Rural Agenda presented in May 2022 the Pact for Circular Fashion. This voluntary agreement has been already signed by 55 companies and entities with the objective to promotes an urgent and necessary transformation of textiles by bringing together all the public and private agents of the value chain [45]. Thus, in order to reduce textile waste in landfills and incineration, and facilitate its recycling, it seems that key to investigate further the flows of textile across the value chain in order to set up measures that ensures an effective impact.

6 Conclusion

The conventional business logic of the clothing industry is based on augmenting production and sales, fast-fashion products, and the increasing sense of consumers' identity; all together these trends generate products' unsustainable design, extreme levels of consumption, and highly uncontrolled waste [22]. For the Spanish territory, textile waste is becoming a relevant waste flow as in other geographies this analysing in detail the domestic production, the imports and exports is relevant to understand better the relevance of the flows and identify those that needs to be addressed more urgently. For example, the high percentage of *synthetic or artificial* materials, which accounts for more than 60%, intensifies the environmental risks related to consumption of water and energy, as well as the emissions generated from the production process. In order to find solutions, the EU suggests environmental rules for textile product design. This translates into product requirements that go beyond energy efficiency, i.e. beyond any product that has an impact on energy consumption during use, pretending durability, reparability, recyclability, creating an EU digital product passport, and tackling the disposal of unsold consumer items [9]. For Spain, as for all EU members, this directive will determine a new vision, to be considered in parallel with Directive 2018/851 for more efficient waste strategies. For the specific case of Catalonia, the Voluntary Pact for Circular Fashion [45] shares the sustainable view of the EU and put together different entities and business experts for transforming the fashion business into a more circular economy.

In addition to regulatory measures at the EU level, moving towards circular and sustainable textiles requires transformation at each stage of the process. Given the highly fragmented value chain, an effort is needed to localise some of the production stages and move towards a more efficient use of resources and the use of, with a materials reusable or recyclable [4]. The purchase of clothing has become very affordable in the last decades, facilitating the accessibility to clothes and exacerbating the effects of this creative industry on the socio-ecological system [62]. The increasing manufacture and consumption affect the global climate, the ecosystems quality, and human health by highly using energy, land, and water. The socio-ecological effects are, though, difficult to address the business model, they generate from, demands speed and supply chain segmentation in location where the price of labour is lower and the accounting, likewise the control, is more complicated [4]. Moreover, these consequences must be intended mostly at a global scale, since with relocation there is almost no local effect and because there are multiple, global impacts when the chain is segmented [63]. Connected with problems related to vertical disintegration and global dispersion ([22], p. 2), the generated environmental risks tend to generate also social effects in the form of social inequality [56] when soil degradation, conversion of natural ecosystems, and waterway pollution hit the ecosystems services of countries where the manufacture has been moved to [64].

In conclusion, reducing the socio-ecological pressures and impacts from textiles production and consumption while maintaining socio-economic benefits needs a systemic change towards circularity, the choice of materials, and the design affect or environment so as behavioural choice [3]. In this regard, providing a comprehensive analysis of the flows and stocks of textile materials is key to envision future textile waste prevention strategies. The consumption rates per person given for Spain and Catalonia would only be reduced with coordinated actions by a range of stakeholders other than the consumers: it requires stronger policies and governance, collaborative design with industries, and education on consumption habits change [7]. A further overarching need, which remains silent but clear along the study, is for clear and complete accountability across the value chain. The main difficulty of this work was indeed gathering transparent and complete information regarding production and trade materials and identifying their significance in the value chain. A possible next step could be the use of the present method to analyse the state of the art of textile section in other EU countries. Obtaining more accurate figures on this topic would help define a roadmap towards a more circular textile value chain.

Acknowledgements This chapter has received financial support from the "María de Maeztu" Programme for Units of Excellence of the Spanish Ministry of Science and Innovation (CEX2019-000940-M) and from the Secretaria General de Recerca i Universitats from the department of Recerca i Universitats (Generalitat de Catalunya), project number: 2020PANDE00021.

References

1. World Bank and World Development Indicators (2017) Euromonitor international apparel & footwear: Vol. Sales trends 2005–15, 2016th ed.
2. Changing Markets Foundation (2021) Fossil fashion. The hidden reliance of fast fashion on fossil fuels. www.changingmarkets.org
3. Ellen MacArthur Foundation (EMF) (2017) A new textiles economy: redesigning fashion's future. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/A-New-Textiles-Economy_Full-Report.pdf
4. United Nations Environment Programme (2020) Sustainability and circularity in the textile value chain global stocktaking
5. Anguelov N (2015) The dirty side of the garment industry: fast fashion and its negative impact on environment and society. Taylor & Francis, Ed.; CRC
6. MODA re- (2021) ANALISIS DE LA RECOGIDA DE LA ROPA USADA EN ESPANA
7. European Environment Agency (2019) Textiles in Europe's circular economy
8. European Commission, & Eurostat (2020) Where do our clothes come from?
9. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions—EU Strategy for Sustainable and Circular Textiles (2022) https://ec.europa.eu/eurostat
10. Circular Economy Action Plan (2020)

11. Köhler A, Watson D, Trzepacz S, Löw C, Liu R, Danneck J (Oeko-Institut and Plan-Miljø) Konstantas A, Donatello S, Faraca G (2021) European commission. Circular economy perspectives in the EU textile sector
12. ModaEs, Moddo, Cityc (2021) Informe economico de la moda en España. https://www.modaes.com/files/publicaciones/free/2021/informe_economico_2021/#page=1
13. Generalitat de Catalunya, CircE interreg Europe, & European Regional Development Found (2021) Circular fashion pact working for a more sustainable future. https://mediambient.gencat.cat/web/.content/home/ambits_dactuacio/empresa_i_produccio_sostenible/economia_verda/Obs-economia/moda-circular/Circular-Fashion-Pact_220419_summary.pdf
14. SECRETARÍA DE ESTADO DE MEDIO AMBIENTE DIRECCION GENERAL DE CALIDAD Y EVALUACION AMBIENTAL Y MEDIO NATURAL (2016) Plan Estatal Marco de Gestión de Residuos (PEMAR) 2016–2022
15. Office for Ecological transition and demographic challenge (n.d.) Specific collecting systems
16. Guerola recycling (n.d.) What is a collection point and what objects are recycled?
17. Caritas (2021) Moda re-published a pioneer informative about the textile waste recycling
18. Generalitat de Catalunya. Departament d'Empresa i Coneixement (2018) OBSERVATORI DE LA INDÚSTRIA: Informe anual sobre la indústria a Catalunya. http://empresa.gencat.cat
19. European Commission (2022) EU strategy for sustainable and circular textiles https://ec.europa.eu/eurostat
20. Sandin G, Roos S, Spak B, Zamani B, Peters G (2019) Environmental assessment of Swedish clothing consumption-six garments, sustainable futures. Mistra Future Fashion. www.ri.se
21. Llorens S (2020) Identificació dels actors i dels fluxos de la cadena de valor del sector tèxtil a Catalunya en el marc del projecte Interreg Europe CircE
22. Niinimäki K, Peters G, Dahlbo H, Perry P, Rissanen T, Gwilt A (2020) The environmental price of fast fashion. In: Nature reviews earth and environment, vol 1, no 4. Springer Nature, pp 189–200. https://doi.org/10.1038/s43017-020-0039-9
23. Needles HL (1986) Textile fibres, dyes, finishes, and processes, a concise guide. Noyes Publications, Ed.
24. Carroll-Porczynski CZ (1961) Manual of man-made fibres. The New Book Company
25. Landi S (1998) The textile conservator's manual, 2nd ed. Routledge
26. Sinclair R (2015) Understanding textile fibres and their properties: what is a textile fibre? In: Textiles and fashion: materials, design and technology. Elsevier Inc, pp 3–27. https://doi.org/10.1016/B978-1-84569-931-4.00001-5
27. Corbman BP (1983) Textiles, fiber to fabric, 6th edn. McGraw Hill International, Ed.
28. Texcoms textile solutions (2019) Textile fibres, Textile Technology knowledge series: vol I
29. Datambient Asesores, Cataluña. Departamento de Territorio y Sostenibilidad, Agencia de Residuos de Cataluña, & Gremio de Recuperación de Cataluña (2015) Guía de Buenas Prácticas - Para el reciclaje de los residuos textiles y de calzado en Cataluña
30. Franck RR (2001) Silk, mohair, cashmere and other luxury fibres
31. European Commission (2019) Best Available Techniques (BAT) Reference document for the textiles industry
32. Long J, Burns K, Yang J (2011) Cloth modeling and simulation: a literature survey. Lecture notes in computer science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 6777 LNCS, pp 312–320. https://doi.org/10.1007/978-3-642-21799-9_35
33. Zillane Patwary M (2012) What is knitting and weaving|difference between knitting and weaving. Textile Fashion Study
34. Fan J, Hunter L (2009) Engineering apparel fabrics and garments. Woodhead Publishing Limited
35. Brunner PH, Rechberger H (2016) Practical handbook of material flow analysis: for environmental, resource, and waste engineers, 2nd edn. CRC Press, Boca Raton
36. Laner D, Rechberger H (2016) Material flow analysis. In: Special types of life cycle assessment. LCA compendium—the complete world of life cycle assessment. Springer

37. White R (1994) In the greening of industrial ecosytems. In: Allenby BR, Deanna RJ (eds) The greening of industrial ecosystems. National Academies Press. https://doi.org/10.17226/2129
38. Villalba G, Iglesias M, Gabarrell X (UAB), Rechberger H, Wien T, Allesch A, Liu G, Cao Z, Kovanda J, Dittrich M, Kulczycka J, Smol M, Cullen J, Brazell S, Olivetti E, Fu X, Müller DB (2018) Concise description of application fields for different MFA approaches and indicators
39. Instituto Nacional de Estatistica (2021) Industrial product inquiry
40. Institut d'Estadística de Catalunya (2022) National Classification of Economic Activities (CNAE-2009). https://www.idescat.cat/metodes/classificacions/cnae-2009-es?lang=en
41. Nam Thai V (2014) Eco-labeling criteria for textile products with the support of textile flows: a case study of the vietnamese textile industry. Conference paper
42. Estadísticas de comercio exterior de bienes de España y la UE (2022) Datacomex. https://datacomex.comercio.es/
43. Palacios-Mateo C, van der Meer Y, Seide G (2021) Analysis of the polyester clothing value chain to identify key intervention points for sustainability. Environ Sci Eur 33. Article number 2 (2021)
44. Hendriks C, Obernosterer R, Muller D, Kytzia S, Baccini P, Brunner PH (2000) Material flow analysis: a tool to support environmental policy decision making. Case-studies on the city of Vienna and the Swiss lowlands. Local Environ 5(3):311–328. https://doi.org/10.1080/13549830050134257
45. Waste Agency of Catalunya (2022) The Pact for Circular Fashion starts, to reduce textile waste in Catalonia, with around fifty accessions
46. Madrid Fashion Capital—MCDM (2021) Acotex presents its report the textile trade 2020, in figures
47. de Maarten VET J, Nigohosyan D, Núñez Ferrer J, Gross AK, Kuehl S, Flickenschild M (2021) Impacts of the COVID-19 pandemic on EU industries
48. Kim S, Woo H (2021) Global fashion retailers' responses to external and internal crises during the COVID-19 pandemic. Fash Text 8(1). https://doi.org/10.1186/s40691-021-00260-x
49. Euratex—The European Apparel and textile confederation (2021) A new EU strategy for textiles & clothing
50. Perry P, Fernie J, Wood S (2014) The international fashion supply chain and corporate social responsibility. In: Fernie J, Sparks L (eds) Logistics and retail management, 4th ed. Kogan Page
51. Karaosman H, Perry P, Brun A, Morales-Alonso G (2020) Behind the runway: extending sustainability in luxury fashion supply chains. J Bus Res 117:652–663. https://doi.org/10.1016/j.jbusres.2018.09.017
52. Chapagain AK, Hoekstra AY, Savenije HHG, Gautam R (2006) The water footprint of cotton consumption: An assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries. Ecol Econ 60:186–203. https://doi.org/10.1016/j.eco
53. Wang L, Li Y, He W (2017) The energy footprint of China's textile industry: perspectives from decoupling and decomposition analysis. Energies, 10(10). https://doi.org/10.3390/en10101461
54. Pesticide Action Network UK (2017) Pesticide concerns in cotton
55. Schönberger H (2019) HAZBREF case studies and sector guidance for the textile industry. Presentation given at Tallinn Conference
56. Bick R, Halsey E, Ekenga CC (2018) The global environmental injustice of fast fashion. In: Environmental health: a global access science source, vol 17, no 1. BioMed Central Ltd. https://doi.org/10.1186/s12940-018-0433-7
57. Iles A (2004) Mapping environmental justice in technology flows: computer waste impacts in Asia. Global Environ Polit 4(4):76–107
58. WRAP (2021) Valuing our clothes: the cost of UK fashion. https://wrap.org.uk/resources/report/valuing-our-clothes-cost-uk-fashion
59. Geissdoerfer M, Savageta P, Bocken NMP, Hultink EJ (2017) The Circular Economy–a new sustainability paradigm? J Clean Prod 143

60. Köhler A, Watson D, Trzepacz S, Löw C, Liu R, Danneck J, Konstantas A, Donatello S, Faraca G, Europäische Kommission Gemeinsame Forschungsstelle (2022) Circular economy perspectives in the EU textile sector final report
61. Generalitat de Catalunya, & CircE Interreg Europe (2021) Circular fashion pact. Working for a more sustainable future. https://mediambient.gencat.cat/web/.content/home/ambits_dactuacio/empresa_i_produccio_sostenible/economia_verda/Obs-economia/moda-circular/Circular-Fashion-Pact_220419_summary.pdf
62. Leading Brands of Spain Forum (2022) Atlas of Fashion. The international footprint of Spanish fashion companies. Retrieved August 18, 2022, from https://atlasmoda.marcasrenombradas.com/files/atlasdelamoda_eng.pdf
63. Mukherjee S (2015) Environmental and social impact of fashion: towards an eco-friendly, ethical fashion. Int J Interdisc Multidisc Stud (IJIMS) 2(3). http://www.ijims.com
64. Granskog A, Laizet F, Lobis M, Sawers C (n.d.) Biodiversity: the next frontier in sustainable fashion. McKinsey & Company.
65. Instituto Nacional de Estadística (INE) (2022) National Classification of Economic Activities (CNAE-2009). https://www.ine.es/dyngs/INEbase/en/operacion.htm?c=Estadistica_C&cid=1254736177032&menu=ultiDatos&idp=1254735976614

Performing Life Cycle Assessment at Scale in the Footwear Industry

Michael Bär, Laurent Vandepaer, Vedanti Shah, and Stephan Pfister

Abstract Performing the life cycle assessment (LCA) of textile products requires detailed knowledge of materials and production processes, and comprehensive information on the downstream life cycle and distribution stages. Design and development teams need complete and robust LCA to understand and reduce the impacts of their products. Consumers increasingly expect textile brands to communicate their environmental footprints at the product level, and regulations are being introduced to make this an obligation in several markets. Providing such a level of analysis per product season after season for entire collections, with sufficient completeness and scientific robustness, requires handling a large amount of data. This task is laborious and repetitive if handled manually with traditional life cycle assessment (LCA) tools or other footprinting platforms. Nevertheless, this process can be accelerated and automated by harnessing existing techniques from the data science/analysis domains and Python-based LCA tools. An approach for an automated and Python-based tool will be presented in this chapter. It was developed to conduct LCA for a footwear brand's current and upcoming collections. The tool consists of multiple programming functions to build data bridges between the existing data infrastructure of a brand and Brightway2, an advanced life cycle assessment framework. These scripts are controlled with a graphical user interface (GUI) to be operated by the design and development teams. The main features are importing expanded bills of materials (BOM), matching this data with primary and secondary life cycle inventories (LCI), merging this with additional LCI not included in BOM to create a full cradle-to-grave LCA model, and then performing life cycle impact assessments, contribution analyses, and local sensitivity analyses to inform the design and development process. Using the results from this approach, designers and developers may introduce new performance indicators to improve their products from an environmental standpoint

M. Bär (✉) · L. Vandepaer · V. Shah
On AG, Förrlibuckstrasse 190, 8005 Zürich, Switzerland
e-mail: michael.baer@on-running.com

S. Pfister
Institute of Environmental Engineering, Ecological Systems Design, Department of Civil, Environmental and Geomatic Engineering, Swiss Federal Institute of Technology, ETH Zürich, Zürich, Switzerland

S. S. Muthu (ed.), *Progress on Life Cycle Assessment in Textiles and Clothing*, Textile Science and Clothing Technology,
https://doi.org/10.1007/978-981-19-9634-4_9

and understand where their product impacts the environment. Once products are ready to go to market, brands can then communicate the final life cycle impact scores of their products.

Keywords Life cycle assessment · Automation · Data science · Product design and development · Python tool · Cradle-to-grave LCA model

1 Introduction

1.1 Goals and Scope

'McKinsey research shows that the global fashion industry produced around 2.1 billion tons of greenhouse gas (GHG) emissions in 2018, equaling 4% of the global total. These emissions are equivalent to the combined GHG emissions of France, Germany, and the United Kingdom. Around 70% of the fashion industry's emissions came from upstream activities such as materials production, preparation, and processing. The remaining 30% were associated with downstream retail operations, the use-phase, and end-of-use activities' (McKinsey & [1].

The fashion and textile industry has come under significant pressure considering its high contributions to global greenhouse gas (GHG) emissions. The industry is expected to maintain the current growth rate and reduce its GHG emissions footprint. With the current growth rate and no environmental improvements, it is estimated that the emissions will rise to around 2.7 billion tons by the year 2030 (McKinsey & [1].

Many companies have become active in reporting their product's environmental performance and have started to establish sustainability teams, which are tasked with developing methods to tackle these environmental challenges. Detailed analysis of a product's supply chain and the entire life cycle is required to identify which phases are significant, and where improvements will have the best effect. A life cycle analysis is a methodologically robust and scientific approach to understanding the processes involved and the system.

Performing a life cycle assessment (LCA) of textile products requires detailed knowledge about the materials and production processes as well as comprehensive information on the downstream life cycle and distribution stages. Design and development teams require complete and robust LCA to understand and reduce the impacts of their products; consumers increasingly expect textile brands to communicate their environmental footprints at the product level. In several markets, regulations are being introduced to make this mandatory. Providing such an analysis for each product, season after season, and for entire collections, requires handling a large amount of data. The analysis requires sufficient completeness and scientific robustness. Conducting this task manually with traditional LCA tools or other footprinting platforms is laborious and repetitive. Nevertheless, this process can be accelerated and automated by using existing techniques from data science and analysis, and Python-based LCA tools.

In this book chapter, a possible approach is discussed. A script was developed to create an automated and Python-based tool to conduct LCA for a footwear brand's current and upcoming collections. The tool consists of multiple programming functions establishing data interfaces between the existing data infrastructure and Brightway2, an advanced LCA framework. These scripts can be controlled with a graphical user interface (GUI) to be operated by the design and development teams. The main features are importing expanded bills of materials (BOM), matching this data with primary and secondary life cycle inventories (LCI), merging this with additional LCI not included in BOM to create a full cradle-to-grave LCA model, and performing life cycle impact assessments, contribution analyses, and local sensitivity analyses to inform the design and development process.

Using the results, designers and developers may introduce new performance indicators to improve their products from an environmental standpoint and understand where their product impacts the environment. Once the products are ready to go to market, brands can then communicate the final life cycle impact scores of their products.

1.2 The Textile Industry's Environmental Impacts and Data Challenges Presented by Product Environmental Footprinting

Given the increasing demand for environmental impact data, some brands have already prepared and published product reports and worked in cooperation with consultancies. These reports describe the methods used to calculate and analyze the products and highlight the limitations. They are helpful for cross-checking the methods and inventories but are usually not similar enough to directly compare the final LCA results. Associations have also been formed to bring the industry together to address some of these issues and limitations. However, due to the complexity of this business, other problems have arisen that have then been criticized.

For single-product LCA, the results are communicated in different ways. Some brands do not give absolute impact values but only percentage improvements over their previous model. Others share absolute values, but these are then presented as a factory-level average and cannot be attributed, unlike a classic attribution-based product-oriented LCA. The Massachusetts Institute of Technology (MIT) conducted the best available LCA for a running shoe in 2012, for an Asics shoe model. It resulted in a CO2 footprint of around 14 kg CO2 per pair of shoes. This study has a low level of detail on the supply chain. Moreover, it is not clear how exactly MIT carried out the LCA and the background information on data sources, assumptions, methodological decisions, and system boundaries is unavailable. These unknowns make a fair comparison with other products impossible. Due to its age, more recent datasets are available, and there have been ongoing developments in raw materials.

Icebug, a footwear brand, recently published a climate footprint of a pair of shoes. Via a QR code, the customer can display the footprint of the selected shoe. With this, they are focusing on transparent communication and better visibility. Another brand, Allbirds, recently analyzed a sneaker's carbon footprint according to ISO 14067:2018 and published the results. The analysis was externally verified and is an excellent example of how to create more transparency in the footwear sector. Allbirds also shared their online LCA tool, which they developed themselves, in collaboration with an external consultancy. With this tool, they try to invite other brands to track and publish the results. The LCA report is publicly available, and the assumptions and baseline data are displayed.

However, Allbirds uses carbon intensities from supplier LCAs and LCA databases. The problem with supplier LCAs and emission factors from databases such as GaBi or the MSI Higg Index is that they often only report the final value, without providing a deeper insight into the model assumptions, system boundaries, parameters, energy, material, and chemical consumption. This again makes it more difficult to question unrealistic or outdated values. It also runs the risk that a overly superficial view is presented, and the further assessment of the supply chain to uncover and correctly interpret hotspots becomes difficult (Allbirds).

These LCAs for a single product are also difficult to transfer to a whole range of products. The Allbrids tool is based on Excel and is designed for user-friendliness. However, the tool is not intended to deal with multiple products. To apply the tool to a whole collection, additional development is required, and this may not be feasible in the same way as for a single product. Prè, the company behind SimaPro, a professional LCA software, has also recognized the issues associated with the increasing demand for environmental footprints and the need for scalable solutions for LCAs of entire collections. The key takeaways from a recent conference are that digitization is needed to reduce the time and cost of LCAs. Digitization requires the development of tools to automate LCAs and better collect primary data for LCAs. Another important finding is that collaboration is needed to achieve digitization and make the most of the technologies and knowledge already available. They are now participating in the EU-funded ECOFACT project to develop a digital platform for LCA [14].

To summarize and clarify, primary data is usually preferred, due to the difficulties encountered with the existing databases. Product LCAs are starting to be published, even if they do not allow easy comparison. The industry has identified the trend to create LCA for more products faster, and now different tools working toward that goal are being developed.

This book chapter presents the inner workings of such a tool. However, the complex topic of collecting and validating data, and quantifying uncertainties is not the focus. This project aims to produce a tool that generates the necessary LCA models, based on which a sustainability analyst could conduct sensitivity and uncertainty analyses in further steps. Such research would also require better datasets that describe these uncertainties more accurately. To generate results, the practitioner must take the data as it is, and the industry and data providers must make efforts in the future to improve these datasets and better describe the uncertainties.

2 Methods

In this section, the programming tools and methods are introduced. The scripts were developed and tested with hypothetical data for different shoe models provided by ON Running.

To generate LCA models for a whole collection and to keep the models comparable, it is necessary that the relevant LCA methodologies remain the same, but key differences in the life cycle of the products can be represented. For each product, the LCA model contains parameters that are different from other products. To implement a system that can generate the different models, specific information on these parameters must be provided.

In the case of our textile products, there are already generalized categories and stages defined by guidelines such as the GHG protocol and the science-based target initiative. A standardized model structure can be generated that also allows for some subparts to be changed according to product-specific data. In the case of our textile products, the variable parts are related to the upstream supply chain and the information required concerns the components of a product and the assembly factories. This information can be provided in a bill of materials with all the required additional information. A Python script can import the bill of materials, which is usually provided in Excel files, and then build up the LCA model, together with additional information on how to link datasets and the general structure. Excel files have the advantage that the data is easily and directly accessible and that it can be transferred as standard files. The automation script has to handle missing data, incorrect data formats, and other user errors. It is also necessary to have a way to predefine and detect the structure of the files. Distinguishing between the different products that are in the same Excel table and which are only separated by, for example, header rows is tricky and may lead to additional problems if the format is changed (Science based Targets & World Resources Institute) [4].

The script combines the different components into one workflow to process the project, the required data, the calculation of the impacts, and the analysis of the resulting impacts.

A simple GUI has been developed to configure and execute the script blocks. The intended end users are the product designers and developers who need a quick and robust tool to perform a sustainability analysis before making decisions about continuing their design cycles.

2.1 Life Cycle Assessment

According to [3] an LCA has four steps, as shown in Fig. 1. The steps are usually conducted in chronological order: proceeding from the goal and scope definition (1) to the inventory analysis (2) to the impact assessment (3), and the interpretation (4).

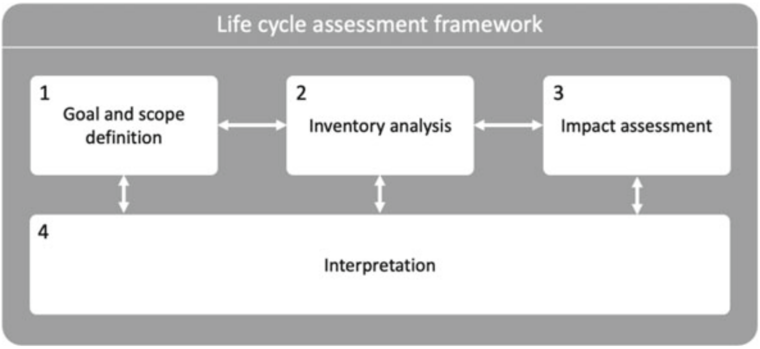


Fig. 1 Steps for conducting a life cycle assessment according to ISO 14040 [3]

At every step, the earlier decisions have to be reviewed and adjusted to fine-tune the whole system and create a best fit for the problem.

Goal and Scope

In the first step, goal and scope are defined. LCA practitioners need knowledge about the system and can first create a material flow diagram to represent the physical flows. They can then expand this initial system and refine it to include other relevant categories, such as energy and water demand. After defining the system, the scope, and the boundaries, the impact assessment methods are defined. In the case of a collection of similar products—and if the product system is general enough—the different products can be based on this system, and only the datasets representing each step are exchanged. Datasets are comparable if they are defined in the same scope and subsystem. The results must be viewed critically if datasets from a background database are used.

In the case of the example shoe data, the modeled system has a functional unit of one pair of shoe models and the scope is from cradle-to-grave (a full life cycle). Initially, the system contained only the upstream supply chain and production. However, the system scope was later extended to the full life cycle, so that transport activities and end-of-life treatment are also included. These downstream activities are also suspected to impact the environment significantly.

Life Cycle Inventory

The crucial part of this work is automating the life cycle inventory creation. Some activities are life cycle phase-specific, and others are fixed, depending on where the production factory is located. The assembly of a product can be represented in detail with information from the bill of materials, which the designers generate. In turn, it is important to analyze whether certain newer versions provide improvements in the different impact categories compared to older versions of a product.

This approach can also be used for other products where the resulting changes in various material inventories are of interest.

The second step of an LCA is to define the life cycle inventory. The system model needs data for the different processes/activities involved and the flows between these and outside the system boundaries. In the case of a more detailed product, LCA primary data from factories and suppliers is combined with secondary and more general data. It is important to remember that there may be uncertainties and systematic errors, depending on how the information is implemented and how good the background data is. In this work, activities modeled in the Ecoinvent database are used as a base in the background. Further datasets from the factories and suppliers are modeled as intermediate activities, which ultimately point to a dataset in the Ecoinvent database. Flows from the technosphere into the biosphere are rarely directly implemented (Ecoinvent [12].

Life Cycle Phases and GHG Protocol Scopes

Initially, the downstream impacts were omitted. However, for a full cradle-to-grave LCA, the downstream emissions are also important. Ecoinvent's cut-off database was used rather than the consequential database. The cut-off data is only concerned with the direct impacts of an activity. In the final system model, the upstream and downstream activities are included, and the decisions on how to implement certain flows can be better followed than with the consequential datasets. The system model is structured around the product LCA model from the GHG protocol, see Fig. 2. In the figure, the categorization into three different emissions scopes and different life cycle phases is shown. Scope 3 emissions may be significant but are not always accounted for in product LCAs. For a holistic picture, the full life cycle should be modeled, and impacts in different categories should be analyzed. For example, GHG emissions during transport, land use for storage facilities, or impacts due to the end-of-life waste treatment may be of interest.

Interpretation of the LCA Results

The results can then be analyzed in table form (Excel) or as plots, where different products are placed side by side. Further, it is also possible to calculate the contributions of different activities to the total score of a product. Here, categories can be assigned according to the scope or life cycle phase, which helps to aggregate the information into a more useful form. Significant contributions can be found, and it is possible to indicate areas of relevance for further investigation, or where improvements may be more impactful.

Fig. 2 Depiction of phases and impact scopes a product has during its life cycle based on the GHG protocol [4]

2.2 Data Sources

Collecting, validating, and modeling primary data from all suppliers and sub-suppliers is a complex process. For the development of the scripts, a foundation of primary data existed. This primary data was always preferred. In cases where such data is not available, literature and database values are used. Furthermore, perfect matching with datasets is not always possible, especially for chemicals. Best judgment is then used to remodel data, based on material safety sheets, or proxies with similar chemical structures are used.

The different assumptions, age of the data, data sources, and the type of modeling and methodological choices have a significant influence on the result. Currently, comparisons can only be made in a benchmarking sense between the different products that are modeled with the scripts.

Primary Data and Data Collection

Ideally, datasets based on primary data from the manufacturers involved are used to model the whole supply chain. However, even for a single product, it is hard to backtrack all steps in the supply chain. A large number of factories are involved in a whole product collection, and the foundation for data collection has to be built up first and then gradually expanded. In the meantime, existing data has to be managed and recollected, when necessary; factory levels and specific factories which produce product components that make a significant contribution to the overall impacts or weights need to be prioritized, as they are the larger levers to introduce improvements. A collaborative approach to work on the topic of environmental impacts and other related aspects is needed to achieve continuous improvement.

Background Databases

There are multiple well-known databases that provide life cycle inventories for different industries. The Ecoinvent database is widely used as it contains a huge number of datasets and is constantly updated. The datasets from Ecoinvent are used as a base to build other datasets. The Ecoinvent datasets have different granularity, and there are general datasets on a global or world level. A limitation of Ecoinvent is that not all datasets have the same quality, and that in some cases the possible detail level could be more specific, as the exact location of a factory is known, but the datasets in Ecoinvent are only available on a global level. Similarly, datasets for some raw materials may be available for a region which does not represent the actual region. In such instances, it might be possible to apply some strategies to adjust the dataset.

Furthermore, there are other databases, such as the GaBi database provided by Sphera and the WALDB provided by Quantis. These are useful, as they are regionalized or more specific for textile materials and textile processing. However, the problem of different cut-off approaches and system boundaries arises. This topic is critical to the validity of the results. There are a few studies related to this topic, and these have discovered that the results for the same LCA model of a product vary depending on the database-software combination, even though the same results are expected. Conducting LCA is still informative and helps find solutions to decrease a given metric. The absolute values of the results, on the other hand, can be misleading and are hard to interpret, even with an acceptable level of uncertainty (Erik [5].

A possible approach to be able to conduct LCAs is to decide on a base database that is only extended with datasets from other databases that have been critically reviewed and analyzed. Also, if primary data is available, and the effort is justifiable, the LCA models can be improved by replacing datasets from any background database with primary data or datasets modeled from more recent reports or studies. An analysis of the changes due to different datasets on different scopes is recommended and a critical approach is needed. The representativeness and validity of data from different sources may vary.

Bill of Materials

The bill of materials is an important part of the input data. Different sources are possible if they provide all the necessary information. An example file format is Excel, which can be easily imported with the Pandas library, which is also used in the script to prepare for building the LCA model.

The bill of materials contains information on the components of a product. The material composition and the name of the product component are needed to identify which datasets are needed in the model. The weight of these component materials is also needed as input values. For a more detailed model, the weight is further split into virgin and recycled material weights, and the number of wasted materials due to quality and process inefficiencies. Therefore, the bill of materials must also declare these shares of recycled content and pattern efficiency. Another important piece of information is the country of origin, i.e., where the components are manufactured. The electricity mix can be adjusted depending on the country, and the transportation of components in the supply chain can be estimated. For the transportation and additional emissions in the assembly factory, this factory has also to be defined per product.

With all this information, the necessary datasets, amounts, and locations can be identified. There are four main types of datasets directly related to the bill of materials. These datasets are for the components that describe the processes at the earlier stages (T2 to T4), waste treatment for the assembly waste, and transportation for bringing the components from T2 to T1 factories (Science based Targets & World Resources Institute).

The bill of material, as well as the component datasets, are usually primary data collected at the factories or by the developers. The data is usually specific to a product during a season. As it is not possible to collect the data every season, tools to monitor the annual performance are employed, and datasets created from previous data collections may be reused to fill the gaps. Transportation and waste treatment datasets are based on background databases, which are regionalized but also more generalized. Adjustments to the transportation and electricity datasets are needed if there are systematic errors or relevant changes due to the age of the datasets and more recent trends. Python is helpful in the bulk processing of the original datasets to adjust them to new biosphere flows.

2.3 Python Development Environment

The processing and automation of the required data can be facilitated with Python and special packages that extend the basic function of Python as a programming language. Since Python is a scripting language, the entry requirements for users and machines are minimal. After installing Python, one can immediately start writing scripts in an editor. This can be a simple editor, such as the pre-installed one on the operating system. The script can then be executed via the console of the operating system.

The development environment was set up with Visual Studio Code. Visual Studio Code makes it possible to work with modular extensions that fulfill a specific function. One extension is Python integration, which enables the management of the various installations of Python kernels with Anaconda3. Another extension provides support for Jupyter Notebook, which would normally need to be launched from the console, and which would then provide a locally hosted online editor. The last important extension is for Git, and this manages the workflow for committing new changes, updating to the latest version, and branching for different sub-projects.

Anaconda is a Python environment management system. It allows there to be different installations of Python and packages for that installation. Anaconda allows for precise control of the versions and increases the reproducibility of the project setup. The package and version list can easily be shared with others (Anaconda [6].

Jupyter Notebooks enhances the script by segmenting the code into blocks. Between the blocks, text for documentation can be added, and the blocks can be executed separately without the need to run all the code every time. The output of a given block is then displayed and saved below the code block. A notebook shares the workspace and its variables with all the contained blocks. This functionality allows for new code segments to be developed more quickly, as the workspace is conserved and can be used by the next block [7].

Git is a version control system. It tracks file changes in a defined directory and its subdirectories, called a repository. The changes can then be committed, and a chronological tree-like structure can be built. Usually, the main branch contains the latest working version, and the subbranches depend on the main branch that contains the newest developments. In this work, Git was used in combination with a private online repository (GitHub), so that the progress can be shared with different people, the project progress can be tracked, and other topics can be handled separately.

A few Python packages are necessary for data preparation, processing, and interpretation. Examples of these are Numpy, Brightway2, Pandas, and Matplotlib. Numpy stands for numeric Python and provides the tools needed for numeric operations and working with matrices. Numpy's core is written in C, which is computationally more efficient than Python. Numpy is efficient and highly optimized for numerical calculation. For this reason, Numpy is often included in other packages such as Brightway2.

Brightway2 is an open-source framework developed explicitly for conducting LCAs. It allows users to benefit from the data pre- and post-processing capabilities of Python and then automate the steps of typical LCA calculations. [8].

Pandas is another crucial Python package. Data importing and exporting from Excel or similar formats, as well as handling this data in a structured form, are its main functions. The conventional data formats of Python do not provide the same functionality, while Pandas has dataframes that can be thought of as Excel table-like structures. There are rows, columns, column heads, and row indexes. The dataframes can be joined, filtered, and grouped with conditions. Other data formats can be converted to dataframes, and vice-versa. The relationship between the life cycle phases and processes are modeled in relational tables in Excel form, and Pandas allows users to work with the information and build the system model dynamically in Brightway2 [9].

The results of the life cycle impact assessment are exported to Excel. To visualize the result, plots are created with Matplotlib. A grid of figures is created and populated with plots of the different impact categories. The formats are predefined, and after the initial testing, the plots will always be created in the same way ready for interpretation. The plotted results can also be saved along with an Excel file containing the results.

2.4 Brightway2

Brightway2 is a whole framework for conducting LCAs. Like the four steps of an LCA, the framework is split up into data handling, calculation, and analyzing modules [8]. When installing the main Brightway2 package, all these submodules are installed as well. Brightway2 is based on projects which will be stored locally in a specific directory. The project is hierarchically structured. A schema can be seen in Fig. 3. Some variables of Brightway2 are globally available in the workspace of the Python kernel, while others are project- or database-specific. In this work, a namespace was defined for these variables to separate them from other variables.

Brightway2 ensures that all the inventories, life cycle impact assessment (LCIA) methods, activities, and exchanges are represented in the databases. The dataset or nodes are linked with each other, and a missing link will cause errors. The databases and projects are saved in a user's local application data store. Brightway2 handles the massive amount of data a life cycle database such as Ecoinvent contains, by converting it into its own structure, as depicted in Fig. 3.

The scripts were developed to automate the creation of additional databases and activities. These activities are linked to other data according to the system model. When creating, updating, and manipulating the data in the databases, Brightway2 methods should be used whenever possible to ensure no invalid exchanges or nodes exist, and that they are correctly stored where they are needed.

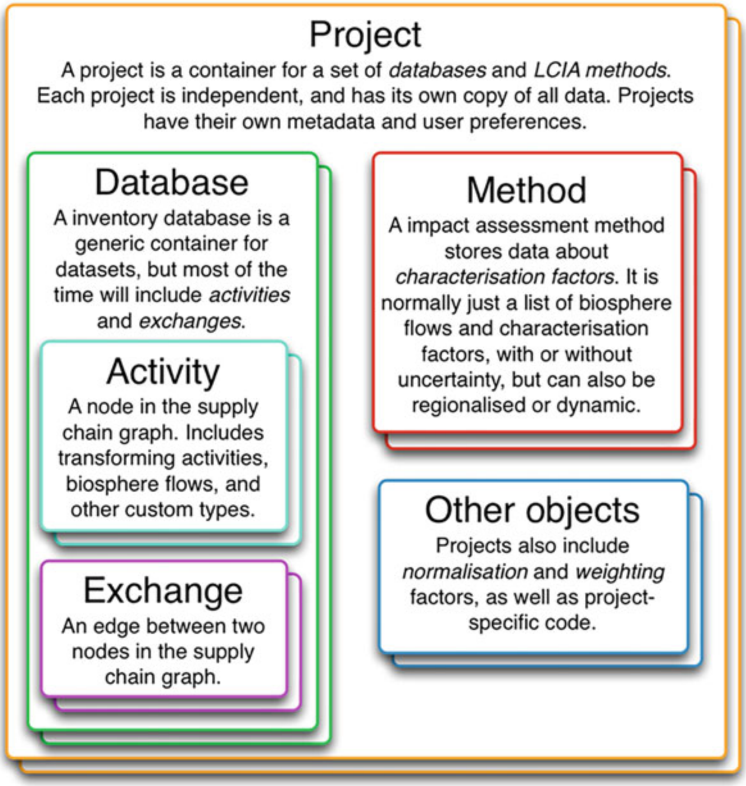


Fig. 3 Schema of the hierarchical organization of a Brightway2 project [8]

A project may be unrecoverably damaged when editing something directly. Regular backups may help, and in the worst case deleting the projects from the file system and starting from scratch is necessary. The scripts developed for this work automated these processes, and the only reoccurring corruption of a project is related to using the activity browser from Brightway2.

2.5 Setup Instructions

The development environment mentioned can be recreated with the following instructions.

The links below are valid and were accessed during April 2022:

- Install the editor VS Code (https://code.visualstudio.com/download)
- Install Git for version control and contributing to repositories (https://git-scm.com/downloads)

- Install Anaconda as Python environment and package manager (https://www.anaconda.com/products/individual).

After installation of these programs, first set up an anaconda environment with all the required Python packages. To do this, open the Anaconda prompt and use the following commands to set up an environment called 'lca_bw2.'

- Conda create –name lca_bw2 python = 3.7.10
- Conda activate lca_bw2
- Conda install -y -q -c conda-forge -c cmutel -c haasad -c konstantinstadler -c pascallesage -c plotly brightway2 jupyter bw2agg bw2calc = 1.8.0 qt qtpy qtconsole

Next, the code editor must be set up and configured.

- Open VS Code and go to the extensions tab (Ctrl + Shit + X)
- Install Python (Python extension for Visual Studio Code) and GitHub (GitHub pull requests and issues) extensions
- Use the GitHub extension to clone a repository locally

Comments for Using the VS Code Editor

The Anaconda3 environment can be selected/changed when editing a file. The dropdown menu is usually in the right upper corner.

The working Git branch can be changed in the bottom left corner, and commits can be managed in the source control window (Ctrl + Shift + G).

3 Results

This section provides a discussion of the developed scripts and functions, and their implementation in a graphical user interface.

First, the system model for a cradle-to-grave life cycle assessment was created. During this phase of the thesis, building up the required knowledge of the system, available data, and the programming environment with Brightway2 were important. Solutions for error handling and how to interface with the data had to be found. Afterward, testing the scripts, interpreting the results, and generating diagrams of the results and the scripts were the focus. It was then decided to extend the system to include processes from cradle-to-grave and start with building the graphical user interface. Both of these tasks required finding working concepts and—especially for the GUI—the effort to find the right approaches was considerable.

In the following section, the resulting concepts and systems are described, the required data inputs and conversion into the model are explained, and a discussion of each of the components is included.

3.1 Resulting in Concepts and Systems

Figure 4 shows the life cycle phases, and the processes and flows during a product lifetime. This is a typical product life cycle, with material production at the beginning and going to end-of-life. Such a system is also called cradle-to-grave. The end-of-life stage is included as waste treatment has a significant impact and, depending on the product, a recycling loop can be included.

In the material production phase, the supply chain of subcomponents and materials is represented. The materials can come from direct resource extraction and pre-processing, or also from recycled materials sources. The recycled sources are modeled with a market mix, where the physical origin is uncertain. For virgin or primary produced materials, the physical source may be defined, but if unknown proxy datasets have to be used there may be other uncertainties. The main categories used were metal, fabrics made from natural materials, and plastics.

The different materials are pre-processed into the components used in the product. In the assembly phase at the T1 factory, all the components are put together and transformed into the final product. At this stage, data collection is feasible, as direct contact of some sort usually exists. Besides the mass flows of the materials, other processes must be accounted for. In the case of a factory, these additional processes are electricity, heating, use of chemicals, detergents, and operation/maintenance of machines. The data collection should examine these details, or they can be estimated. The operators of the factory provide a detailed list of what is used and needed to keep the factory running. Such information is available for other purposes and may even have been already collected with a data collection tool.

The additional processes and materials used in a factory are used as a shell, where the materials that are provided by the bill of materials are omitted. The bill of materials of a hypothetical product can then be added to this data and linked to the material production from the life cycle phase that happened before. This approach can be repeated for different designs of a product or other products in a collection. It is also possible to investigate any change that is introduced by production at different factories.

For a cradle-to-gate system boundary, the modeling of these upstream activities in the supply chain would be sufficient. However, the impacts stemming from downstream activities also contribute significantly to the total score and the whole life cycle should be considered with a cradle-to-grave system boundary (McKinsey & [1]**.** To extend the system boundary, after the assembly, the distribution and storage phase, the use phase, and the end-of-life treatment have to be added to the system. Information on the market shares of the sales and trade routes is used for the distribution routes. The use phase for a product contains the processes and activities a customer performs. In the case of our shoe models, it was assumed that only washing the shoes is relevant. Selling the shoe and processes happening during the use phase are based on the Mistra Future Fashion report (Gustav [10]. Customer traveling distance can be adjusted with the assumption of the behavior of customers in different markets. In the last phase, at the end of the life of a product, there are limited options: The

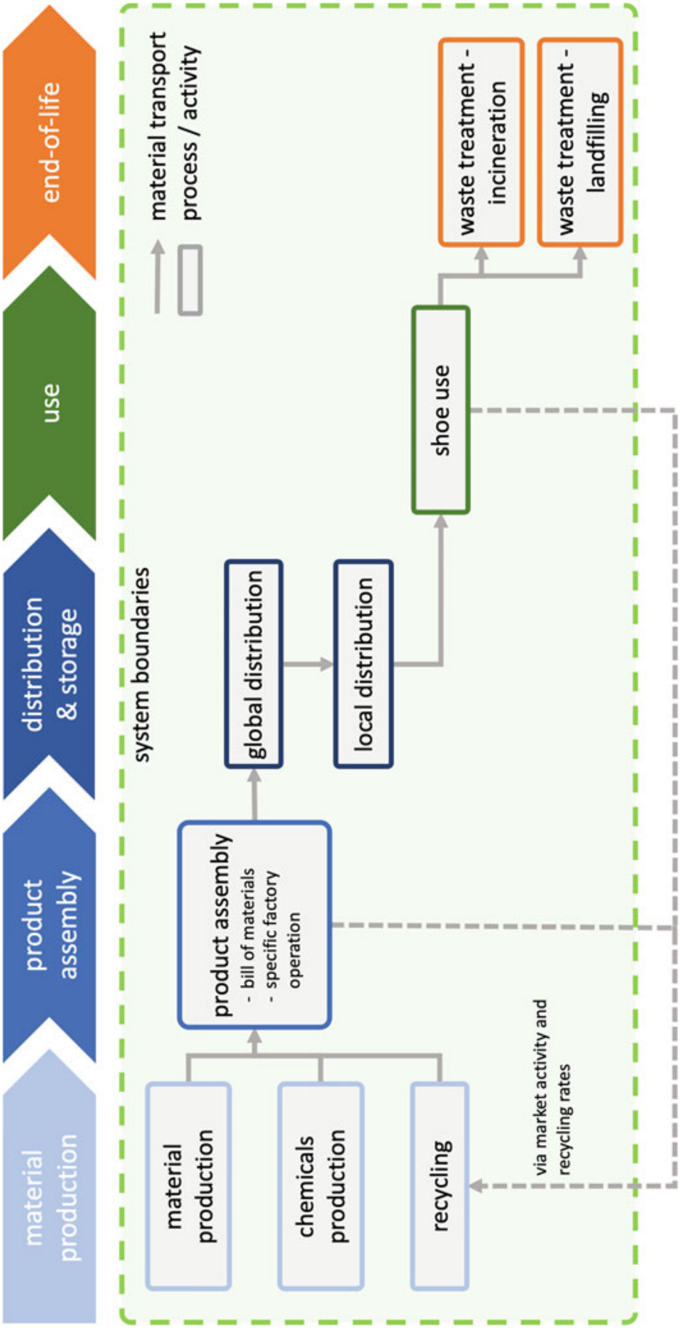


Fig. 4 Diagram of phases, processes, and flows during the lifetime of a product

product can go to waste treatment or be recycled into raw materials. Depending on the region where the use and the end-of-life phase occur, shares for which type of waste treatment are used can be included.

Recycling is not directly modeled, but a share of the materials can be reused and reenters the raw materials market, which are then used to manufacture new components for products. The share of recycled material is provided along with the bill of materials, and increased recycling scenarios can be formulated by adding the same product, but with changed recycling rates. In a truly circular product, the material of that product is recycled again into the same product. Such a material flow is not guaranteed, and the quality of the recycled material may be too low to be reused in the same product category. Also, complete control over all the processes in a circular system is hard to achieve, and modeling via a market is more realistic.

3.1.1 Steps and Workflow of the Python Script

Figure 5 presents a visualization of the steps performed by the script to create the life cycle inventory in the Brightway2 project. The boxes in orange represent the steps themselves and are also equivalent to the code blocks in the Jupyter Notebook and the main functions that can be triggered with the graphical user interface. On the left side, the data sources can be seen as inputs and on the right side, there are the outputs. In the central box, the steps that perform an action with the Brightway2 framework are visualized inside the green box. The green box also represents the Brightway2 project schema from Fig. 3.

The following steps need to be conducted to process the input data into an LCA model and to generate results:

1. Setup and preparation for a Brightway2 project
2. Import of background databases and inventories
3. Import of bill of materials and life cycle-model information
4. Preparation of data for the LCA model
5. Generation of the LCA model in Brightway2
6. Calculation of LCA results with different impact methods for all products
7. (optional) Calculation of the contribution analysis for specific products
8. Saving the results and visualization.

The following steps should be conducted in chronological order.

First **(1)** the Brightway2 project has to be initialized by defining a project name and then executing the setup function of the project. This will automatically create the necessary local file structures, set up the database interface, and create the biosphere database with the required entries. After the setup is completed, the impact assessment methods can be defined and linked to the biosphere. This is necessary so that, when conducting the impact assessment, the relevant flows to the biosphere are known and can be quantified and attributed to the impact assessment method.

In the second step **(2)**, the required base and reference data have to be imported. This data describes the processes and transformations that are happening during a

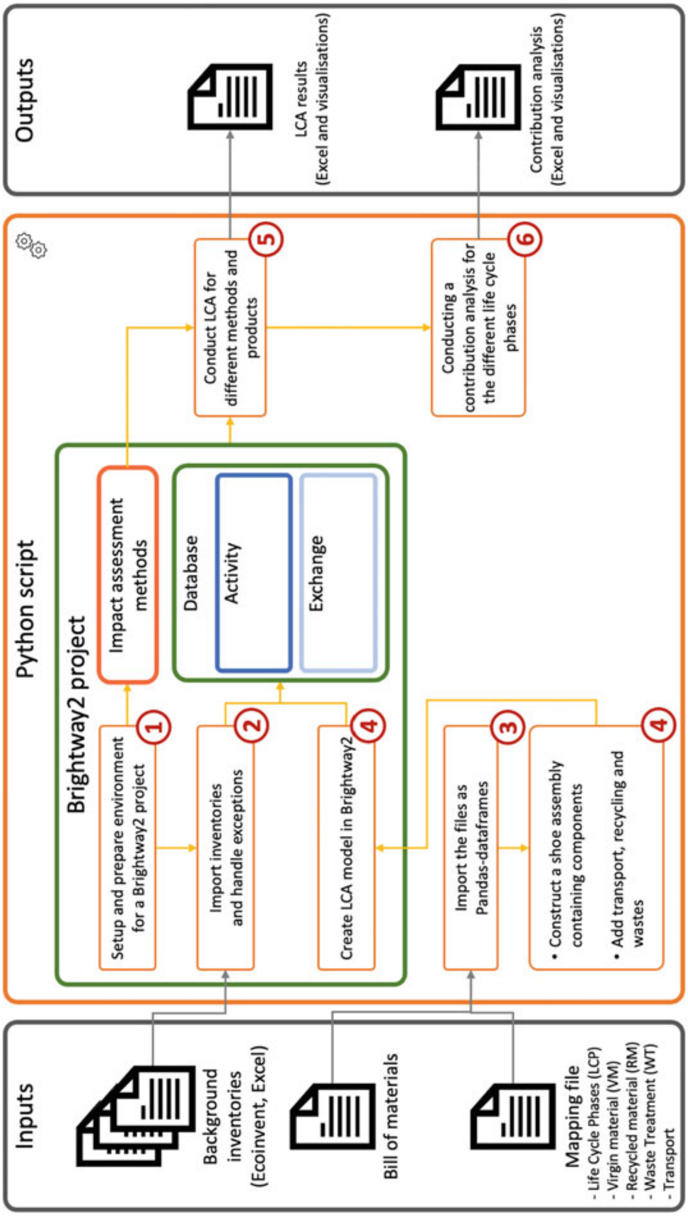


Fig. 5 Schematic of the steps and data processing during the creation of product models in Brightway2 and computing the life cycle impact scores of these models

product's lifetime. The import method depends on the file formats and is realized in the script for the ecoSpold format used by Ecoinvent and as a bulk import for the Excel files that represent the factory operation data, material, and chemicals datasheets. For all these imports the dependency is relevant. The Ecoinvent database must be imported first, because the subsequent databases from the Excel files are linked and depend on the data in Ecoinvent.

The bulk import can find the correct order itself, but this process is faster when a list with a correct import order is provided. The newly imported databases are checked for invalid exchanges. Such exchanges are mostly caused by linking directly to an end node in the biosphere database or because the activity that needs to be linked does not yet exist for the specified location. These exchanges will then be linked to a corresponding activity from another location. This mismatch of location will later, in step **(4)**, be checked and resolved by recreating the activity at the correct location and changing to the correct electricity mix.

The third step **(3)** is to import the bill of materials from the product developers and designers, and the mapping file. The mapping file is specific for each modeled system. When generating LCA models for different products in the same collection, the mapping file describes the possible options for datasets and how to model the assembly process, logistics, and end-of-life activities. The bill of materials changes for different products and with that, the upstream supply chain can be different for every product in the collection. The import of the bill of materials is into the Pandas dataframe, which then allows for further data processing. The input data is checked for inconsistencies. For example, the cell values of some columns need to be numeric or convertible to a numeric format, so that in step **(4)** the shares of the material types can be correctly calculated. Incomplete rows are excluded to reduce the computational effort and avoid problems later. The user will be warned and can input valid, complete data. The script can continue without the excluded data, but the product model will be incomplete. Handling of these special cases is not implemented.

From the imported data, the activity hierarchy shown in Fig. 6 can be created. Before the LCA model of the product can be constructed inside the Brightway2 project, the necessary activities for the 'product component'- 'material' combinations have to be found in the mapping file. The Pandas dataframe can, similar to a SQL database, join or add columns to the table depending on preexisting information in each table row. For virgin materials, recycled materials, transport, and waste treatment, Pandas can quickly do a merge or left join operation with the mapping files. The identifier is the component-material combination provided for each component. The bill of materials has entries for the material name, country of origin, weight, material loss rate, and recycling rate. With these rates, the total material amount that is input into the assembly process can be calculated for each material, and from there the absolute amounts of virgin and recycled material are derived, as are the amounts that go to waste treatment and the distances that the material was transported before it arrived at the factory. The following calculation logic is used to derive the different amounts. For a different structured bill of materials, the calculations will change.

The dataframe containing all the information is checked for missing links or other conflicts. The script will alert the user in the console about such cases, while the GUI

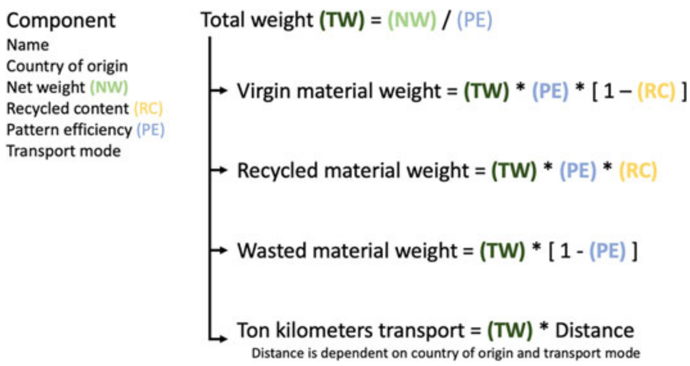


Fig. 6 Calculation logic applied to information in the bill of materials

will display a dialog window with options to resolve the conflicts. The main source for missing links is that a certain combination is not defined in the mapping file, or the combination cannot be identified due to spelling errors in the material names.

The code in the Jupyter Notebook can create the product as a full LCA model from cradle-to-grave or cradle-to-gate. A switch in the code can be set to true, which then adjusts the system model. If a full LCA is conducted, the Excel sheet 'life cycle phases' provides a list of activities that happen additionally and expands the system to the full life cycle. In that Excel sheet, the product model uses the additional processes according to which factory produces that product. Different markets can be defined, and the number of products attributed to each market is computed automatically or with the defined market shares. The amounts of the activities from the life cycle phases sheet can be multiplied by the total weight of the product, if the correct syntax is used in the unit of these activities.

The script then is entered into the Brightway2 project and creates the mentioned activity hierarchy. The exchanges or flows need an activity to link to in the existing life cycle inventory of the Brightway2 project. The lookup process is implemented with a function to quickly search the different databases and find the correct activity by name and location. The name of the activity representing a given 'product component'-'material' combination is defined in the mapping file. The location is given by the country of origin defined in the product's bill of materials. The results of the searches are stored in a Python dictionary for future use. If the same activity can be reused, the lookup process can be significantly improved by looking up the stored matches. The search function is not as fast as this approach. If no activity matches the activity name and location, the same activity is searched without trying to find the exact location. The activity found in this way is then copied, and the electricity dataset is exchanged with the one corresponding to the new location.

The product LCA models are created in a new database called 'product models.' This database contains the activity hierarchy for each product. The highest level of the hierarchy represents the full life cycle and can be used in step **(5)** to conduct the LCA calculation.

In step **(5)**, the Brightway2 framework creates the necessary matrices and solves the linear equation systems. The different assessment methods can be applied, and the results are saved into a Pandas dataframe for each product and each impact assessment method. The dataframe containing the results can be saved to an Excel file. For product comparison, a diagram visualizes the results as bar charts. An example of six hypothetical shoe models is shown in Fig. 10. These diagrams are helpful for visual inspection, comparison, and presentation of the different results. Product variations can be analyzed by providing a different bill of materials for different scenarios. Material composition and top contributors can be identified and assessed with a contribution analysis.

3.1.2 Activity Hierarchy, Data Origin, and Data Usage

In Fig. 7, the activity hierarchy is visualized with colored boxes showing the activities. These are the activities in the database 'shoe models' inside a Brightway2 project. Also visualized and outlined with the gray dashed line is the data origin and the activity in which that data is used. The file icon and captions below provide more information about the data type used. The operation of the whole script is described, and the data processing is described in step **(4)** above.

At the top of Fig. 7, the hierarchy levels can be seen for the activities that have to be newly created or linked. Level 0 represents one shoe model. In the database, one activity for each shoe is created. The activities from the lower level are linked to their parent activity by defining them as exchanges in the parent activity. The exact name, location, amount, and unit of the child's activity must be known. Therefore, the activities are created in parallel so that they can be found and linked. At level 1, the life cycle phases are represented. The color of the boxes corresponds to the life cycle phase color in Fig. 7.

These activities are used to group the following levels and are relevant for the contribution analysis. The information on creating the first two levels stems from the mapping Excel file and the two sheets: 'life cycle phases' and 'waste treatment.' Different factories and user markets can be defined, as well as waste treatment methods for the materials per treatment type.

At level 2, the activities created from the factory operation collection sheets, and materials and chemicals data sheets are linked to their life cycle phases. Some activities at this level require information from other activities at other levels. The amounts for the different materials going to waste treatment and the total weight of a shoe model are used to calculate the ton kilometers for the transport and how many kilograms of material is incinerated or landfilled during end-of-life waste treatment. Similarly, the kilogram amount of a pair of shoes is required for the factory operation method. From the data collection sheet of a factory, the emissions and material use over a year of operation are known, and the impacts per kilogram of shoe minus the material used for the shoe are calculated from this data. The removal of the materials allows only the supporting processes of the factory to remain in this dataset. This factory processes dataset can also be averaged over a longer timespan to provide

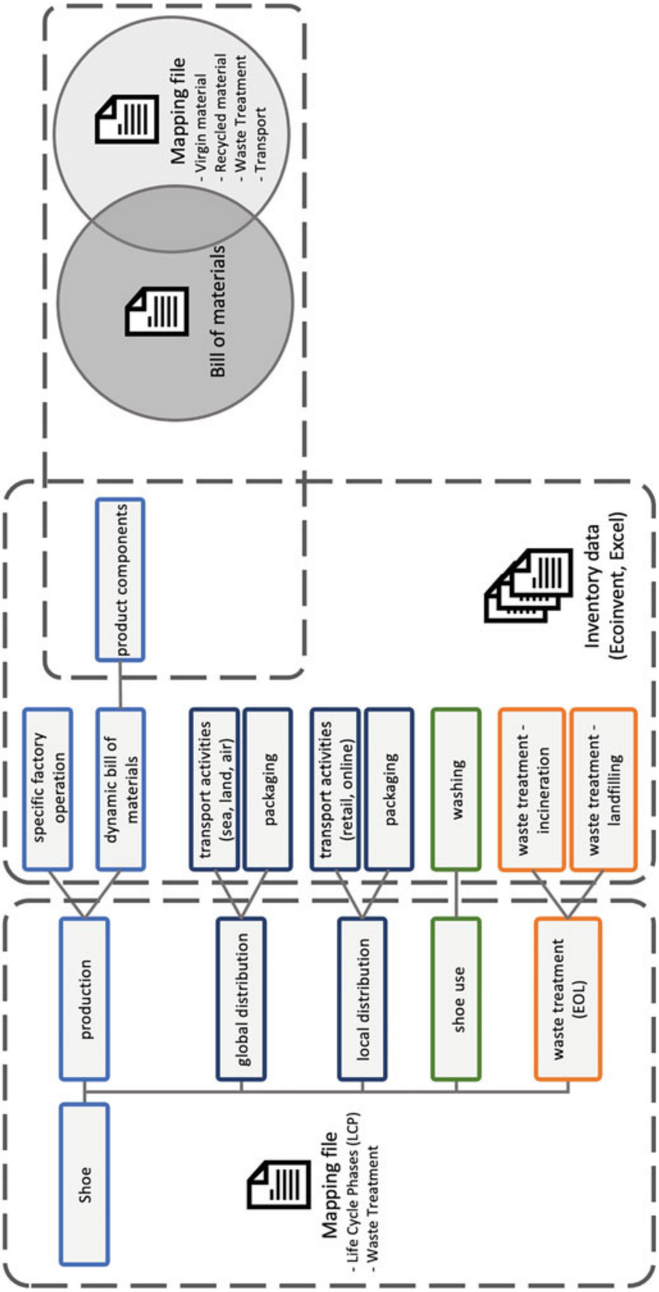


Fig. 7 Data origin, pre-processing, and usage to build the shoe models in a Brightway2 project

more representative values. The components of another product can then be added to this dataset, resulting in a new model of a complete product.

These materials for a hypothetical product are the bill of materials provided by the product designers. At level 3, the subcomponents are located and linked to the bill of materials at level 2. The calculation of the correct amounts is complicated. First, the script merges or left-joins the data from the bill of materials with the data from the mapping file. The information about the material weight, the share of recycled material, and loss of material during the production come from the bill of materials, and the activity names for material production, waste treatment, and transport are in the different sheets of the mapping file.

At levels 2 and 3, the custom activities are saved in their databases in the Brightway2 project. The data is imported from the inventory Excel files located at inventory\custom data. The exchanges of activities at levels 2 and 3 and the custom activities are linked to the Ecoinvent database. These activities also have a further hierarchy, which is not displayed in Fig. 7.

The contribution analysis can traverse these hierarchies and go through the levels recursively. Information on dependencies and types of exchanges can be used to aggregate the results and produce insights into the origin of the impact.

3.2 Graphical User Interface

The intended users for the graphical user interface are designers, developers, and sustainability teams. It can also be used by anyone who wants to automate their life cycle assessment. In that case, a degree of effort is necessary to change the functions that read the Excel files for the bill of materials.

It is also important to think of other setups; it is not always the case that the designers and developers can generate the LCA results in themselves. A simpler solution can be sufficient if the users are proficient with Python. The sustainability team members can use the scripts as a tool to quickly generate the results.

Below, a possible implementation of a GUI is described. The main features are that the different code blocks can be used without any prior knowledge of Python, so that feedback is provided for manual validation and adjustments, and to manage the results. The GUI uses the same Python package as the activity browser from Brightway2. This package is called pyqt5 and allows the creation of windows, dialogs, buttons, and more. (Qt [11].

Figure 8 shows the main window of the GUI. At the top, the three views or modes of the GUI are accessible with the three buttons. The views are:

1. Project settings (first step)
2. Shoe models (second step)
3. Life cycle impact assessment (third step).

A new project will start with the project settings view and the user must complete certain steps before enabling the other views.

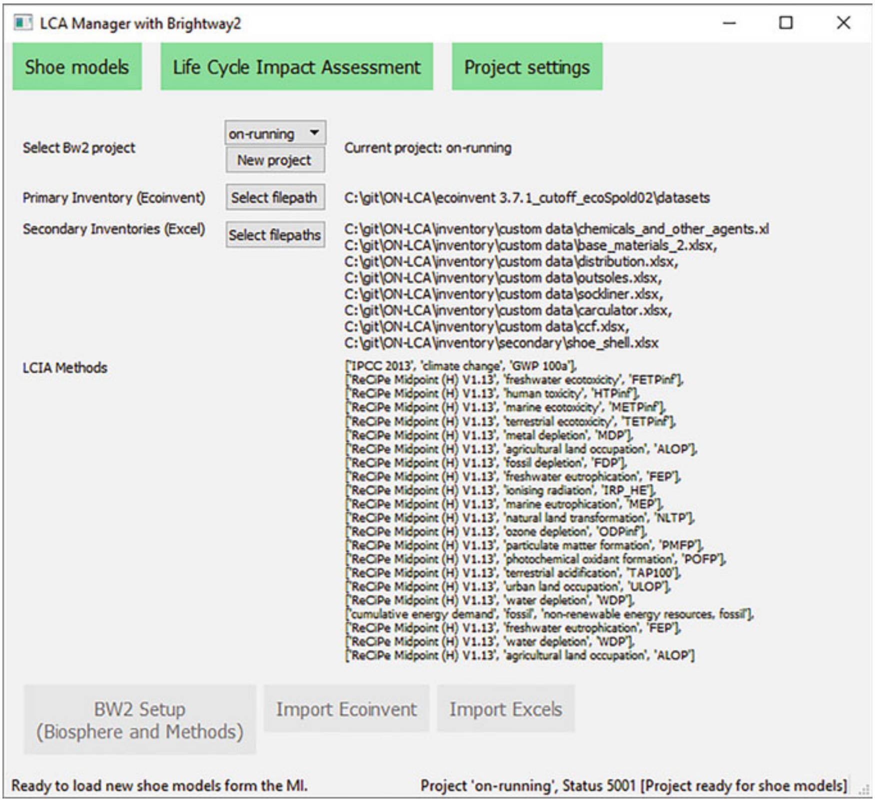


Fig. 8 The first view of the GUI displays the settings for the project and lets the user set up a new project

The whole GUI uses a state machine to track the progress and enable and disable the correct buttons. The current project and status code can be seen in the status bar at the bottom. This also displays a description of the status and of what can be done next. The state machine controls the metadata in the background. It checks what information is defined in the project and what Brightway2 databases are set up to determine the current status.

A Brightway2 project can be set up in the project settings by choosing a name and clicking the first button on the bottom left. Then, the inventories can be loaded. For this, the directory and file paths have to be given. A dialog box for selecting these will open when the respective buttons are clicked. The impact assessment methods are also displayed but must be changed in the config files.

In the second view (Fig. 9), the bill of materials and the mapping files can be defined and loaded. In addition, the data preparation, handling, and creation of the activity hierarchy are controlled here with the four buttons below the file path selection. The progress is reported per category in the bottom part of this view. The four

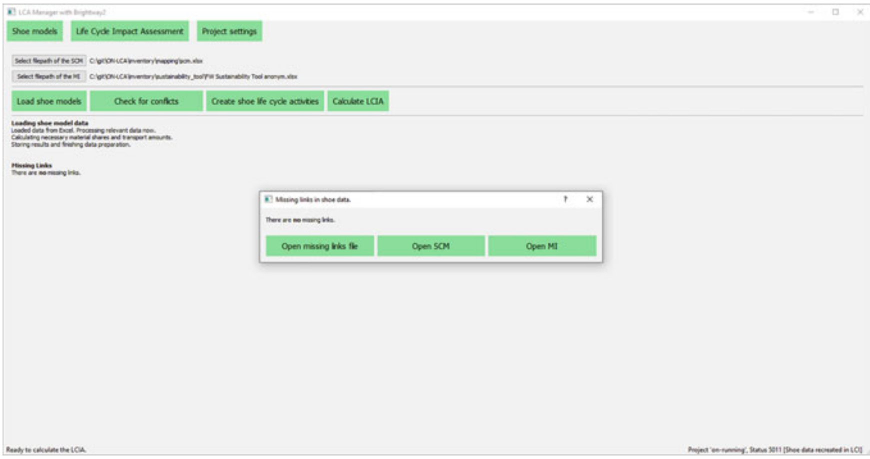


Fig. 9 The second view of the GUI gives controls to import the shoe material inventory and mapping file

buttons are connected to steps 3 and 4 in the script. The button ‘check for conflicts’ allows checking of the bill of materials and the linked activities from the dataframe, which will then be converted into the activity hierarchy. A warning will be displayed if there are any undefined links or amounts that could not be calculated. In the dialog box that opens after checking for conflicts, there are the options to open the missing links in Excel. This Excel contains more detailed information about which links were not found. Depending on the type of error, the user must adjust the bill of materials Excel or the mapping Excel. The dialog also provides two buttons to access the correct files directly. After the corrections are inserted, the first step of ‘loading the shoe models’ has to be repeated. Afterward, the activities can be created. This process will ignore shoe models with missing links. The progress report shows the shoe model currently being worked on and what activities require additional handling.

The more time-intensive operations are handled by creating subprocesses or threads to avoid blocking the main window. However, as the subsequent steps are not yet available, the controls will be blocked with a transparent overlay. The progress is updated during the runtime of the parallel tasks. A short description indicates what the program is working on; for example, the creation of the activities.

The last button in the second view of the GUI allows the user to perform the life cycle impact assessment. The view will be switched to the results window (Fig. 10) and the results will be saved both to Excel and as an image of the created diagrams. On the left side, the current and previously generated results are displayed, and controls to switch between the results and two preview options are given. The main area of this view shows the preview of the Excel tables and the diagrams.

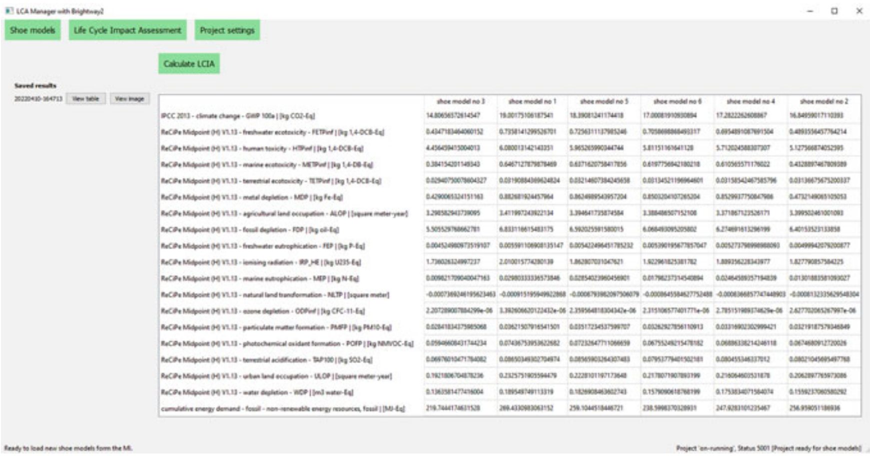


Fig. 10 The final view of the GUI shows the current and previously generated results and gives controls to switch between them and the two preview options (table or image)

3.3 Performance and Limitations

Performance is always taken into consideration. However, some operations could still be optimized further. These operations are mainly the creation of the more extensive databases in the Brightway2 project and the search or lookup of the activities that will be linked during the creation of the activity hierarchy. The database import takes up to ten minutes for the Ecoinvent database. However, this import is only performed once at the beginning, during the Brightway2 project setup. The search function for looking up the activities in the Brightway2 databases is improved by creating a Python dictionary that stores the results of previous lookups. This dictionary helps to reduce the time for creating the activity hierarchy for six products from around one minute to eight seconds for six products.

The informative value of the results is limited by the data, the assumptions made, and the activity mappings. The accuracy and validity of this data need to be considered, as does the potential impact of these inaccuracies. This question should be considered for the intermediate data of the factories, the data of materials and chemicals, and, in general, the data in the background databases (Ecoinvent). For the Ecoinvent database, some uncertainties are quantified in pedigree matrices for the activities. With a Monte Carlo simulation, the probability and range can be assigned to the total impact scores at the end. The problem then becomes more complicated, and the need for accurate data and information about the uncertainties increases. For future improvements of the developed tools, the inclusion of such considerations is recommended.

The setup of the systems for different products is limited because some aspects are not sufficiently generalized in the script. The import of the bill of materials is specific to the sustainability reports from ON. It is still possible to change the required table column names in the script and adjust the calculations. Then, scripts will also work for other products. Automation of the interpretation of the results could be extended with predefined specific contribution analyses.

The scripts were developed and tested for material inventories of fictitious shoe models provided by ON. The bill of materials is extracted from the sustainability report that the designers and developers can generate themselves. Allowing user input means that the script must be adjusted for different material inventories of other products. Moreover, data from a typical Vietnamese textile factory was used to test the automation and the GUI.

3.4 Results Visualization

3.4.1 Model Comparison

Figure 11 shows the results for six example shoe models of different compositions from the same factory, and with the same two markets in the downstream life cycle phases. Each impact assessment method has an individual plot, and the shoe models are arranged side by side. Plotting the results this way allows for visual inspection and interpretation of the different methods and shoe models. The magnitudes of the impact scores can also be important and require more background information to be categorized.

The script generates both the results table and the diagram from the life cycle assessment results and saves them in Excel and image formats. The GUI allows the preview of these results, this preview is based on these saved files.

3.4.2 Contribution Analysis

Another approach for interpretation is an analysis of the contribution of the different activities to the total impact score. The script has a function to recursively descend the activity hierarchy levels until a maximal recursion depth is reached, or the impact scores fall under a cut-off value. This contribution analysis function takes a shoe model and an impact assessment method as an argument and computes the impact scores for this combination. The resulting contribution value, and information about the activity and its predecessors in the hierarchy, are saved in an Excel table. The Excel table allows further inspection by creating a pivot table. This table can then group the activities by, for example, the life cycle phase or category defined during the creation of the activities. A filter for the recursion level or hierarchy level is required to obtain the correct results and, with the contribution levels, the most impactful category can be found. Using the sum of the contribution values, the degree to which the total impact score is reduced due to the cut-off value can be determined. If this sum is higher than one, the calculations will be incorrect, or multiple recursion levels are counted together.

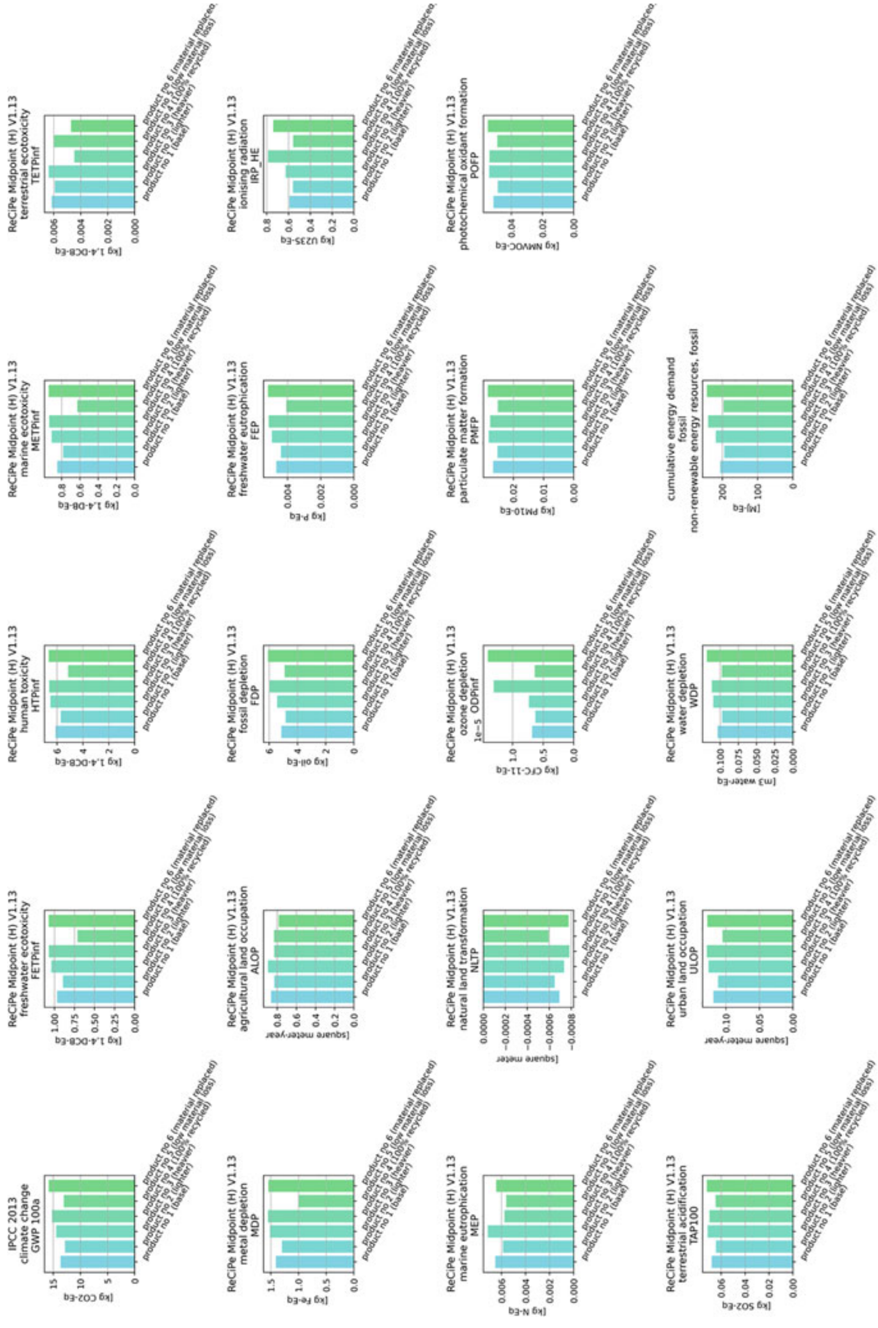


Fig. 11 Visualization of the LCA results with bar charts for each impact assessment method and all modeled shoe models

Figure 12 presents another visualization of a contribution analysis. This analysis function takes a shoe model as an argument and simultaneously computes the impact scores for all the defined impact assessment methods. The life cycle phases' contribution to the impact assessment method's total impact score is displayed. Because the life cycle phases are always the same and the contribution values are relative to the total score, they can be plotted in this stacked bar chart. Peculiarities in the different impact assessment methods can be found. For example, with this test data, terrestrial ecotoxicity, agricultural land occupation, and ionizing radiation have different life cycle phases that contribute more to the total score than the other impact assessment methods.

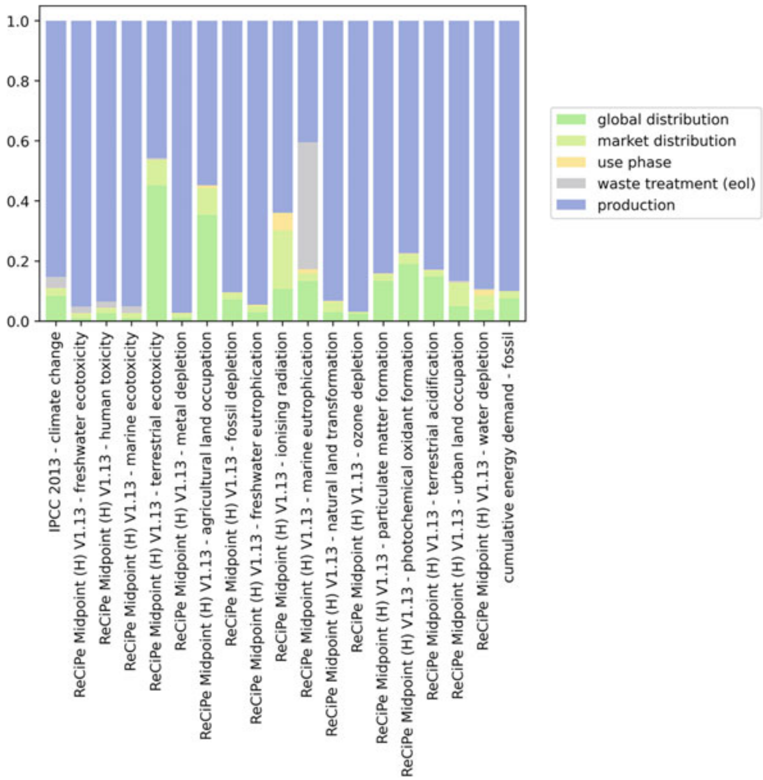


Fig. 12 Contribution diagram for several impact assessment methods applied to one shoe model and grouped by life cycle phases

4 Conclusion

It is possible to automate many tasks in an LCA. With the right tools, such as Python and Brightway2, the results for a hypothetical shoe model can be computed and prepared for analysis in a meaningful way. Product designers and developers can use the results and information generated with such tools to make decisions about their products. This information extends the basis of performance indicators with an environmental viewpoint of their product and will be helpful when improving a product and reaching predefined environmental goals.

The setup and preparation of the necessary data and system model, as well as the validation of the results, will still require an expert. For rapid and iterative improvements in the product design stage, this automated approach helps and simplifies the workflow. It is possible that the final product design and decisions taken will be reviewed at the end of the development cycle by sustainability or environmental experts. During the development cycles, involved persons can make better-informed decisions on whether an adjustment to a component or an improvement in another parameter has a positive environmental impact.

Data scientists and researchers make extensive use of Python. In this project, impacts on performance when handling large amounts of data were already noticeable. Sophisticated programming and implementation are needed to reduce the computation times to acceptable levels. The script would need to be improved even further for a higher number of products, more extensive bills of materials, or more complex system models. The computational effort multiplies with the number of activities included in the system. Parallelization of the operations and outsourcing to other platforms will have to be considered. One such example is Numpy, a Python package that uses C ++ at its core for better performance or multiple threads to prevent the locking up of the GUI.

For researchers, the tool—and especially the scripts—are helpful as a base for a more specific analysis of the results and system dynamics. By changing how the activity hierarchy is generated, scenario analysis, sensitivity analysis, and system optimization for a given product may be possible.

References

1. McKinsey & Company. (2020) Fashion on climate—how the fashion industry can urgently act to reduce its greenhouse gas emission
2. Science based Targets & World Resources Institute. (n.d.). Science-based targets guidance—apparel and footwear sector.
3. ISO 14040. (2006). Environmental management—life cycle assessment—principles and framework. Int Organ Stand, Geneva
4. Greenhouse Gas Protocol. (2011) Product life cycle accounting and reporting standard
5. Erik Pauer BW (2020) The Influence of database selection on environmental impact results. life cycle assessment of packaging using GaBi, Ecoinvent 3.6, and the environmental footprint database

6. Anaconda Inc. (2021, 10 15) Anaconda documentation. From https://docs.anaconda. com/
7. Jupyter Team. (2022, 08 01) Jupyter project documentation. From https://docs.jupyter.org/en/latest/
8. Mutel C (2022) Brightway2: Introduction and key concepts. From https://2.docs.brightway.dev/intro.html
9. Pandas development team (2022) Pandas documentation, version 1.4.2. From https://pandas.pydata.org/docs/
10. Gustav Sandin SR (2019). Environmental assessment of Swedish clothing consumption—six garments, sustainable futures. Mistra Future Fashion
11. Qt Company (2022) Qt for python: Documentation. From https://doc.qt.io/ qtforpython/
12. Ecoinvent Association (2020) Data releases: ecoinvent v3.7.1. From https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-7-1/
13. Allbirds. (n.d.). Allbirds carbon footrprint Report—Futurecraft.Footprint
14. Prè sustainability (2021) LCM 2021: How do we scale up LCA? From https://pre-sustainability.com/articles/lcm2021-scaling-up-lca/

Review of Microfibres from Various Industries and Its Life Cycle Burden on Environment

Nagireddi Jagadeesh and Baranidharan Sundaram

Abstract When it comes to researching ways to extend a product's useful life while decreasing its negative effects on the environment, this generation has always been at the cutting edge of civilization. An environmental impact assessment is a part of life cycle assessment that looks at how a product or service affects the environment. Microplastics (MPs) are classified as primary and secondary MPs, where the primary MPs such as plastic pellets, beads and fibres are synthesized and added to various daily life products such as toothpaste, cosmetics, pharmaceutical products, road paints and vehicle tyres. Secondary MPs are derived from the weathering of various larger plastics whose size is greater than 5 mm by the effect of wind, light and UV radiation. The release of primary MPs into the environment is due to the disintegration of textiles during washing, wear and tear of automobile tyres, release of pharmaceuticals and personnel care products (PPCPs) into the environment. Regardless of their source MPs are becoming an emerging threat to environment and biota due to their non-biodegradability nature and remain in the environment for longer duration. A life cycle assessment (LCA) was used in this study to determine the energy, water requirements and associated environmental impacts caused by Microfibres and the associated energy use. The environmental impacts of the Microfibres are assessed using life cycle impact assessment (LCIA) for the following impact categories such as (a) Global Warming Potential, (b) Primary Energy Demand (PED), (c) Water Consumption. The study focuses on the LCA of MPs and their pollution across the various compartments of environment such as atmosphere, sediments, salts, fresh and salt water and soil. MPs are well-known for their ability to carry hydrophobic organic pollutants, and there are rising worries about their potential environmental and human health impacts. Despite the lack of research, the present study attempts to link various features of MPs, their origins, interactions, and effects on pathogens, organic, inorganic pollutants, biota, aquatic species and humans.

N. Jagadeesh · B. Sundaram (✉)
Department of Civil Engineering, National Institute of Technology Andhra Pradesh, Tadepalligudem, Andhra Pradesh, India
e-mail: baranis@nitandhra.ac.in

S. S. Muthu (ed.), *Progress on Life Cycle Assessment in Textiles and Clothing*, Textile Science and Clothing Technology,
https://doi.org/10.1007/978-981-19-9634-4_10

Keywords Microplastics · Microfibres · LCA · Energy · Water · Environment · Pollution

1 Introduction

Plastics were the great innovation of the twentieth century, and they've been used in a variety of industries because of their high strength-to-weight ratio and low cost. The global data for plastic consumption has been increased exponentially from 1.5 million tons (1950) to 360 million tons (2018), as per Statista's statistical data [4]. The basic classification of plastics is done based on the size range, microplastics whose size >2.5 cm, followed by meso plastics 2.5 cm to 5 mm, and microplastics whose size is in the range of 0.001 to 5 mm [17]. MPs had become a global issue; these were found in almost all pharmaceuticals, paints, cleaning products and personnel care products (PPCPs), including facial creams, soaps, body lotions and tubes of toothpaste [40]. Based on their source MPs are classified as primary and secondary, primary MPs are synthesized and used in the products such as cosmetics, textiles, drugs and toot pastes as an add on, and the secondary MPs are formed due to continuous weathering and disintegration of macro and meso plastics under the influence of UV radiation [3, 10, 11, 39]. The sources of secondary MPs are originated from fishing nets, packaging materials such as plastic films, PET bottles, food and beverage, and plastic trash from residential and commercial settings [11, 26, 35, 37].

MPs are widely distributed across the world and frequently identified in soil, marine and freshwater sediments and wastewater [8, 19, 33, 39, 45]. MPs' have been identified in aquatic and terrestrial ecosystems and are being ingested by various species [18]. Ingestion and entanglement of MPs in aquatic and terrestrial ecosystems through food chain cause potential health risks such as starving, and immune functional issues [42]. Also, the interaction of MPs with organic and inorganic pollutants in the environment results in leaching of chemicals and heavy metals which ultimately affect the organisms residing in the respective ecosystems [24–26, 36, 39, 41]. These are new challenges in society, and the majority of the reports have come from MPs concerned about pollution, which has become a public concern in the last decade. The environmental implications of plastic pollution have gained widespread attention in recent years. However, until far, there has been no focus on how plastics are controlled from a life cycle viewpoint and how regulatory loopholes might be closed to reduce plastics' impact on the environment threatening effects of both large and small plastics.

Concerns about the potential for MPs to concentrate persistent organic pollutants and their role in trophic transmission among marine species pollutants (POPs) is developing at this time. Researchers have seen a transport of MPs between micro- and macro-scale zooplankton from crabs to mussels; however, no particle biomagnification has a food chain detection. Inherent contaminant transfer, including the spread of when a person consumes MPs tainted with POPs or another hydrophobic pollutant, several researches have shown marine biota. Maybe this produces problems and poses a threat to the environment. It is still unclear how organisms are exposed to contaminants (Syberg) and others. One of the leading causes of plastic waste in the ocean and, by extension, MPs—current European Union (EU) interest is plastic carrier bags. LDPE is the primary plastic used to make shopping bags (Andrady 2011). There are now prohibitions or restrictions in place in some countries. Plastic bag tariffs have reduced use to as low as 90% decreased reliance on them throughout the European Union (Convery et al. 2007). In reality, however, not every nation has the same tax rates or there have been laws put in place and concerns voiced about plastic It's possible that carrying bags contribute significantly to the amount of trash produced in the (Cozar et al. 2014) seas. Extensive research has been done to better understand the phenomenon and results of littering with disposable plastic items. Examining, probing and trying to understand under the frames of the laws that seek to restrict pollutants (MPs) into the environment is a developing field related to the scientific method. There is an urgent need to address this issue since plastics are hard to get rid of after they've entered the water: once the trash pollution has reached the ocean, it will be there for a long time. There is a lot of time between steps in the deterioration process. Most plastics are brittle and will shatter easily until the point when the plastic is broken down to the microscopic or nanoscale level where it can only be broken down further after a lengthy wait, mineralization is complete. The fracturing into tiny pieces and dispersing them globally makes ocean clean-up exceedingly difficult, if not impossible. Hence, investigating methods to lessen plastic waste is the greatest alternative for lowering plastic pollution and at what point in the LC of plastics the issue might arise a greater effort be made to address before it becomes marine trash.

1.1 Microfibers in Environment

Microfibers may enter the marine water column and sediment biogeochemical pathways and food webs due to their tiny particle size and extensive spread. Although our knowledge of microfibers is still immature, it is critical to determining plastic's environmental destiny and its remediation in these channels [5]. Recent years have seen an enormous amount of study across several sectors, which has improved our knowledge, but it is clear that the results must be streamlined and consolidated. The biogeochemical significance of microbe-fibre interactions is examined in this section, based on information from laboratory and field research [5]. In particular, new methodologies and analytical approaches are being focused on in order to better understand how microorganisms and microplastic litter interact in a two-way fashion and the resulting environmental consequences [31]. Plastics are concerned as a growing emerging threat to the environment, which contaminates air, soil, water and food and on an average a person consumes 5 g of plastic through various ingestion pathways such as drinking water, consumption of various aquatic species and inhalation of air [7].

1.2 MPs Pathways into the Environment

Plastics were the great innovation of the twentieth century, and they've been used in a variety of industries because of their high strength-to-weight ratio and low cost. The global data for plastic consumption has been increased exponentially from 1.5 million tons (1950) to 360 million tons (2018), as per Statista's statistical data [4]. The basic classification of plastics is done based on the size range, microplastics whose size >2.5 cm, followed by meso plastics 2.5 cm to 5 mm, and microplastics whose size is in the range of 0.001 to 5 mm [17]. Microplastics (MPs) had become a global issue; these were found in almost all pharmaceuticals, paints, cleaning products and personnel care products (PPCPs), including facial creams, soaps, body lotions and tubes of toothpaste [40].

MPs are widely distributed across the world and frequently identified in soil, marine and freshwater sediments and wastewater [8, 19, 33, 39, 45]. MPs' have been identified in aquatic and terrestrial ecosystems and are being ingested by various species, and ended up in human body as shown in Fig. 1 [18]. Ingestion and entanglement of MPs in aquatic and terrestrial ecosystems through food chain cause potential health risks such as starving and immune functional issues [42]. Also, the interaction of MPs with organic and inorganic pollutants in the environment results in leaching of chemicals and heavy metals which ultimately affect the organisms residing in the respective ecosystems [24–26, 36, 39, 41]. These are new challenges in society, and the majority of the reports have come from MPs concerned about pollution, which has become a public concern in the last decade. Figure 3 shows the pathway of MPs into the environment through various phases and ultimately affects humans.

1.3 Life Cycle Assessment

A life cycle assessment (LCA) tool developed in compliance with ISO 14040 and ISO 14044 methodology was used to evaluate the environmental performance of any product or apparel made out of various materials [2]. This study considers the emissions from extraction, manufacture, production, use, recycling and end of life of materials which are taken into consideration by the LCA (Fig. 2) [23]. The inventory phase of this study is critical, since it comprises data collection in order to measure effects and evaluate desired changes [14]. A products' entire life cycle must be examined in order to acquire a complete picture of its energy consumption and environmental impact and to uncover potential strategies to improve its sustainability over time [21].

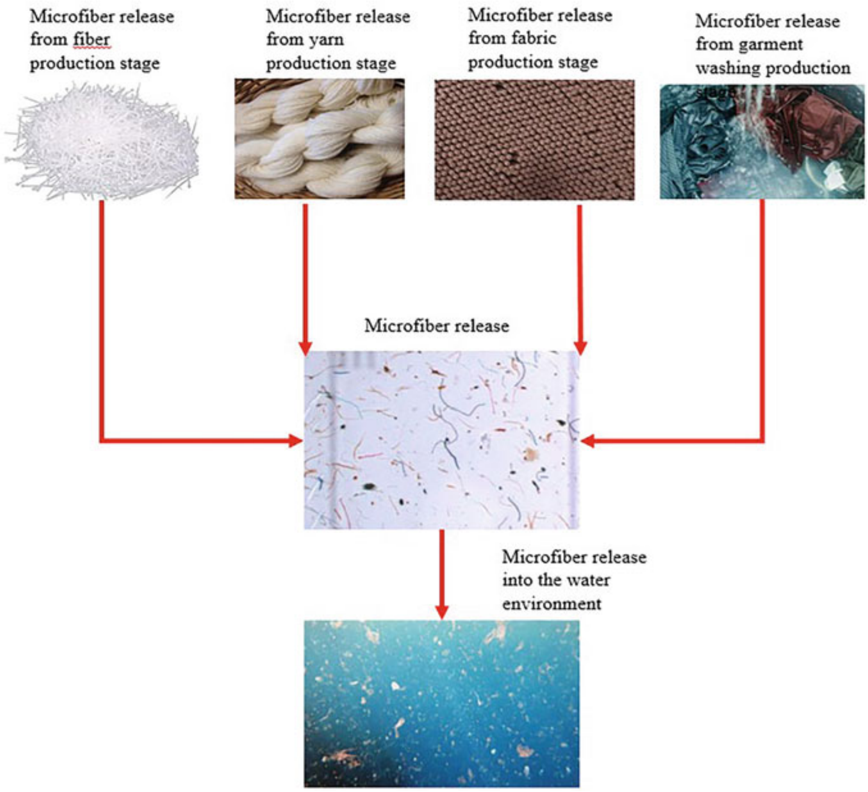


Fig. 1 Microfibre release into environment

1.3.1 History of LCA of Microplastics

There are many studies across the globe that comprehended the MPs and their existence in the environment in different forms. It would be difficult to perform LCA of secondary microplastics, which are originated by the influence of natural sources like degradation and disintegration of macroplastics with the help of UV radiation, release of microfibres from textiles washing and all these ultimately end up in the environment causing health threats to humans, animals and aquatic species. So far there are many LCA studies conducted in macroplastics used for packaging, beverage, food and fashion textiles and none of the studies were done comprehensively on the LCA of primary MPs (such as Pellets, fibres, nurdles, fragments, and foam). Table 1 shows the various LCA studies performed so far on the macroplastics such as PE, PP, PET, PA and polyurethane (Table 2).

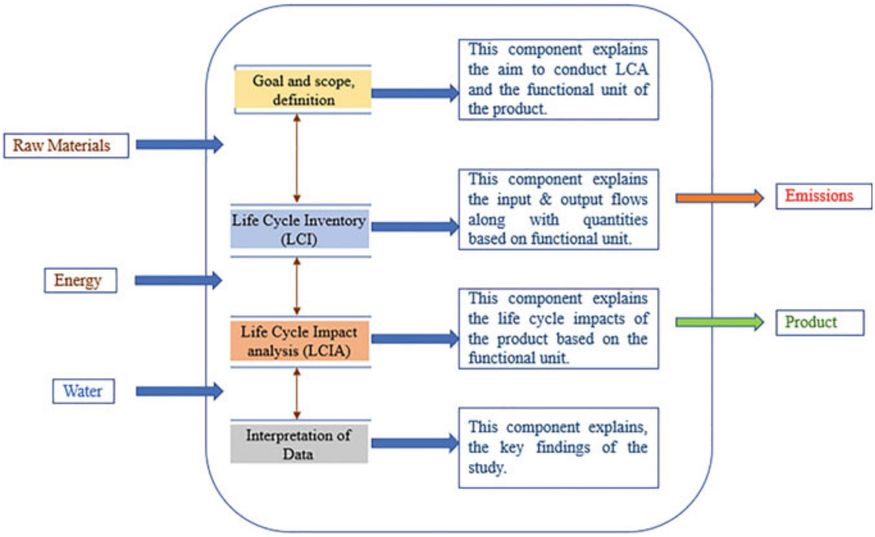


Fig. 2 Chart for LCA methodology

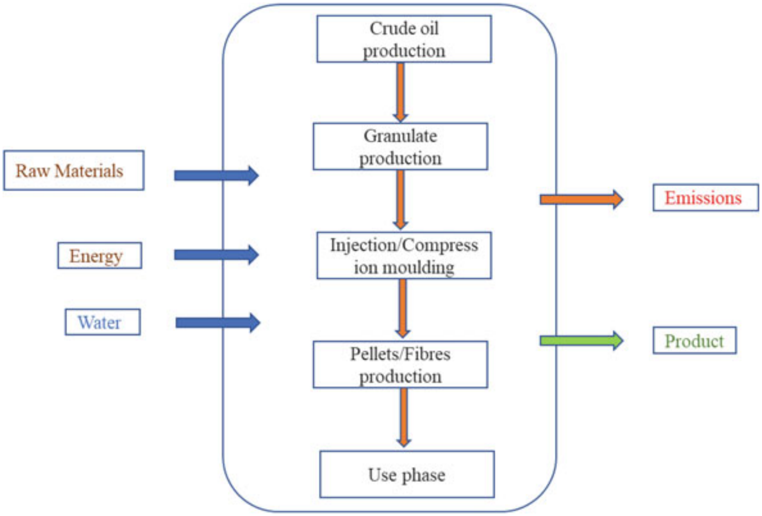


Fig. 3 System boundary for production of virgin microplastics for various uses

1.3.2 Goal and Scope Definition

Over the last two decades, several companies in the textile and clothing industries have begun to apply Life Cycle Assessment (LCA) to a larger degree. With the help of LCA, you may get a comprehensive manual for finding procedures, alternatives

Table 1 Recycled polyester/polyester

S. no	Author's	Goal	Functional unit	System boundary description	BWC (kg)	GWP (kg CO_2 eq)	PED (MJ)
1	[27]	The objective is to assess the environmental impacts of the postconsumer PET bottles mechanical recycling life cycle, to understand the differences of the recycled PET products	1 kg of PET fibre	Cradle to Gate	144	27.2	125
2	[32]	The objective is to assess the environmental impacts of the postconsumer PET bottles mechanical recycling life cycle, to understand the differences of the recycled PET products	1 ton of rPET waste	Gate-to-Gate	–	2.82	48
3	[15]	The goal of this project was to analyse the environmental impacts of Green2O bottles by assessing 4 types of plastic materials including ENSO, PLA, 100% recycled PET and regular PET	The functional unit denoted for this project was 12 bottles, as this amount is typically found in one pack of Green2O water bottles	Gate-to-Gate	–	3.58	55.5

(continued)

Table 1 (continued)

S. no	Author's	Goal	Functional unit	System boundary description	BWC (kg)	GWP (kg CO_2 eq)	PED (MJ)
4	[12]	The objective is to assess the environmental impacts of the postconsumer PET bottles mechanical recycling life cycle, to understand the differences of the recycled PET products, B2B and B2F, in a Brazilian context, comparing them with products from other regions and analysing the systems of products studied to propose environmental improvements	(Recycled waste to 1 ton of fibre)	Gate-to-Gate	11.7	1.218	4.4
5	Zamani et al. (2015)	The intention of the study is to identify possible recycling technologies and determine whether the suggested recycling techniques for household textile waste could potentially result in a net environmental benefit, compared to current practices	The functional unit used in the calculations is waste treatment for 1 ton of household textile model waste by each technique or by a combination of the three recycling techniques to minimize waste for incineration	Gate-to-Gate	4.87	0.9	26

Table 2 Polypropylene (PP)

S. no	Author's	Goal	Functional unit	System boundary description	BWC (kg)	GWP (kg CO_2 eq)	PED (MJ)
1	[1]	The main goal of this LCA study is to quantify the environmental impacts associated with the manufacturing process of PP, based on a case study that has been implemented for an existing PP plant located in the GCC	One ton	Cradle to Gate	–	1.58	–
2	Viktoria Mannheim et al. (2020)	The goal of this research work was to propose an injection-moulding technology that can provide environmentally friendly engineering solutions	One kg	Cradle to Grave	–	1.27	0.664
3	[22]	The scope of this study includes the comparative investigation of carbon footprint of plastic, paper, non-woven and woven shopping bags in both cradle to gate and grave states from the data sources mentioned above in China and Hong Kong	1 plastic bag of (6 g)	Cradle to gate and grave	–	0.001169	0.403

(continued)

that are easier on the environment, and choices to make. The findings of many studies are retained inside the confines of an organization or a corporation, and LCA creates interpretations in compliance with International Standard Organization (ISO) regulations. While there has been an uptick in LCA research as of late, most of the findings on textile items' LCA have so far been confined to academic journals. Therefore, there are insufficient open-source literatures and Life Cycle Inventory

Table 2 (continued)

S. no	Author's	Goal	Functional unit	System boundary description	BWC (kg)	GWP (kg CO_2 eq)	PED (MJ)
4	[22]	The scope of this study includes the comparative investigation of carbon footprint of plastic, paper, non-woven and woven shopping bags in both cradle to gate and grave states from the data sources mentioned above in China and Hong Kong	1 PP fibre non-woven bag of (65.6 g)	Cradle to gate and grave	–	0.472	0.0911
5	[22]	The scope of this study includes the comparative investigation of carbon footprint of plastic, paper, non-woven and woven shopping bags in both cradle to gate and grave states from the data sources mentioned above in India	1 Plastic bag of (6 g)	Cradle to gate and grave	–	0.00116	0.40
6	[22]	The scope of this study includes the comparative investigation of carbon footprint of plastic, paper, non-woven and woven shopping bags in both cradle to gate and grave states from the data sources mentioned above in India	1 PP fibre non-woven bag of (65.6 g)	Cradle to gate and grave	–	0.472	11.15

(LCI) databases to assemble more research investigations. The effects of the textile industry's recent trend of decentralizing manufacturing to developing nations are significant enough that they must be included into LCA analyses. The research in this case involves a supply chain spanning from Pakistan to France. In addition, cotton curtains were chosen as a textile product to measure LCI flow throughout manufacture and consumption. Last but not least, recording all the inputs (including energy, water, etc.) and outputs of each stage of the production-consumption cycle is essential for an accurate evaluation of environmental consequences. Large-scale pollutants in the atmosphere are measured, including carbon dioxide (CO_2), sulphur dioxide (SO_2), nitrogen oxides (NOx) and other particles.

Various textile goods have had life cycle assessments conducted, with attention paid to certain procedures. Because of this, researchers have delved deeply into the topic of spinning energy. An inventory-based analysis of polyester textiles has been conducted, and the weaving process has been studied from an LCA viewpoint. As a result of academics and professionals constructing their own datasets by mixing information from secret, varied and some extremely ancient sources, it has become difficult to authenticate the core dataset sources. In spite of the abundance of LCA studies on the textile industry, few of them provide enough coverage of the whole textile value chain. There is a lack of production-specific LCI data required for full LCA calculations and hence, incomplete LCA calculations. The purpose of this research was to plan for a future Life Cycle Assessment by determining which phases of the service and product life cycles had the greatest environmental consequences based on the life cycle inventory.

LCA was used to calculate the environmental impact and energy consumption. The functional unit (FU) is the area of the floor space in m^2 with a 50-year life span included in this study. The building's life cycle, which is separated into three segments, includes all of the phases of construction, operation and demolition (end of life). SimaPro PhD v9.0.0.49 was used to estimate the impacts; this being an educational version of the licence in which the expert utilizes all of the functions available to other experts [13, 20]. The impact analysis was carried out using the ReCiPe Midpoint v1.1 method (H), a Hierarchist method using Ecoinvent v3.0 (database inventory), which has an international acceptance across the world. The following impact categories were taken into consideration: (a) Global warming potential (GWP), (b) Stratospheric ozone depletion (SOD), (c) Fine particulate matter formation (FPMF), (d) Ozone formation (OF), (e) Terrestrial acidification (TA), (f) Freshwater eutrophication (FE), (g) Marine eutrophication (ME), (h) Terrestrial ecotoxicity (TEC), (i) Freshwater ecotoxicity, (j) Marine ecotoxicity, (k) Human carcinogenic.

Functional Unit (FU)

The functional unit of the study is defined as 1 kg of micro fibre/plastics that are produced for the use by consumers. These microplastics are produced by polyethylene (LDPE & HDPE), polypropylene (PP), polyamide (PA), polyurethane and acrylate majorly for the various purposes.

System Boundary

In order to determine the possible environmental impacts of a product, process or activity from its inception through its eventual disposal, a cradle-to-grave LCA is conducted. Figure 3 depicts all the processes and system boundaries of this investigation. There are many steps in the microplastics/fibres production chain, but the most crucial ones are as follows: (a) crude oil extraction, monomer and polymer production; (b) the granulate production; (c) injection/compression moulding; (d) pellets/micro fibre production; (e) packing; (h) shipping. (a) sale, (b) use and recycling (with considerations for external factors like power and detergent production), and (c) disposal, landfill, and incineration make up the consuming phase.

1.4 Life Cycle Inventory (LCI)

1.4.1 Data Collection

Data collection is the critical process in LCI, and it's not easy to obtain the data easily. Data collection can be done in two ways such as primary and secondary types of data.

Primary Data

This can be done by the following methods

- Visiting and observing the fields/ industries/factories
- Conducting Surveys
- Preparing questionnaires
- Conducting Interviews
- By conducting real-time experiments

Secondary Data

This can be done by the following methods

- Peer-reviewed journals or article data
- Public records
- Statistical records
- Technical and Business documents

The data obtained in any of the above methods are used in the LCI to initiate the modelling using existing software such as SimaPro, GaBi, and Open LCA which would help in the validation and analysis. Benchmarking of the data is a smooth process which would support the analysts to validate the obtained data to overcome the critical review issues. The Bench marking can be done by comparing the primary/secondary data with similar existing project data/peer-reviewed articles.

1.4.2 Transport

Each destination treatment centre was predicted to be situated within a certain distance, for example, kilometres of the landfill. Ecoinvent 16–32 t lorry, EURO-4 process models were utilized to simulate the vehicles' movements [38]. Figure 4 shows the transportation involvement in production of various types of synthetic granulates.

1.5 Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) is a methodological tool for determining the significance and magnitude of potential environmental system impacts [29]. It is a technique in which inventory data is associated with various impact categories in order to gain a comprehensive understanding of the features. Some of the LCIA internationally accepted and predominantly used methods are

- CML 2001 (Latest CML 2016 Aug)
- Eco-indicator 99
- IMPACT 2002 +
- ReCiPe (Midpoint)
- IPCC
- TRACI
- Ecological Footprint

The purpose and scope of the study dictate the impact assessment methods, and in some cases, LCIA must be adjusted accordingly. There are numerous established

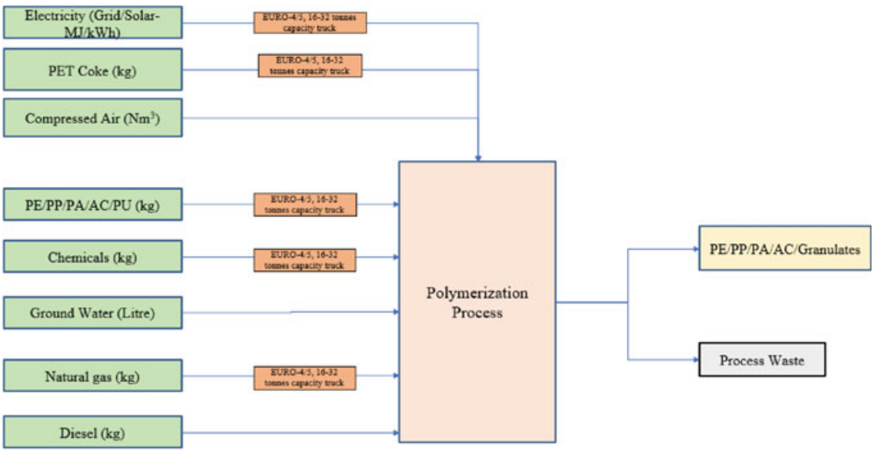


Fig. 4 System boundary for raw material transportation and granulate production

methods for conducting an impact assessment study and some of the steps to follow for choosing the assessment method.

- Picking the right impact categories
- Categorization: placing the primary flows in their appropriate effect groups
- Characterization: modelling probable consequences using conversion factors to create an indication for the impact class
- Optional Step 4: Normalization, which involves describing possible effects in relation to some kind of reference
- Optional Step #5: Classify Impact Metrics by Group
- Optional weighting: assigning different values to different effect categories; assessment and reporting

1.6 Life Cycle Interpretation

Life cycle interpretation is the systematic approach to analyse the LCI and LCIA impacts. These results are summarized and put forward the better decision from these summary impacts [23] (Table 3).

1.7 Recycling and Disposal Options

The waste generated in each process is sent for final disposal or recycling with the similar waste material.

1.7.1 Recycling

Recycling is the best possible treatment to minimize the waste sent for disposal. The waste produced after the use phase as shown in Fig. 5 is sent to disposal have either send to disposal or recycling.

Recycling is the best technique to reuse the waste and converts waste into useful product, which reduces the environmental burden by replacing the virgin material production [34]. Waste recycling starts with collection and sorting, followed by polymerisation, injection moulding to produce the plastic resin, which can be used as virgin plastic resin as shown in Fig. 6. The recycling of synthetics can be done in two methods named as mechanical and chemical recycling [28] based on best available techniques with respect to the cost and environmental benefit.

Table 3 Parameter's equivalent to different impacts

Impact category	Units	Parameters
Global warming potential (GWP)	kg CO_2 eq	Carbon emissions
Stratospheric ozone depletion (SOD)	kg CFC11 eq	
Ozone formation (OF)	kg PM2.5 eq	Air quality
Terrestrial acidification (TA)	kg NOx eq	
Particulate matter formation (PMF)	kg SO_2 eq	
Marine eutrophication (MEU)	kg P eq	Water quality
Freshwater eutrophication (FEU)	kg N eq	
Terrestrial ecotoxicity (TEC)	kg 1,4-DCB	Human health
Freshwater ecotoxicity (FEC)	kg 1,4-DCB	
Marine ecotoxicity (MEC)	kg 1,4-DCB	
Human carcinogenic toxicity (HCT)	kg 1,4-DCB	
Human non-carcinogenic toxicity (HNCT)	kg 1,4-DCB	
Fossil resource scarcity (FRS)	kg oil eq	Fuel resource scarcity
Blue Water consumption (BWC)	m^3	Water quantity

Mechanical Recycling

Collection and sorting: It is a process in which all the waste plastics is collected and sorted from other mixed waste.

Shredding: In this process, the sorted plastic waste is shredded mechanically into small pieces.

Polymerisation: In polymerisation process, the shredded plastic waste is melted by supplying heat/steam to produce recycled plastic resin.

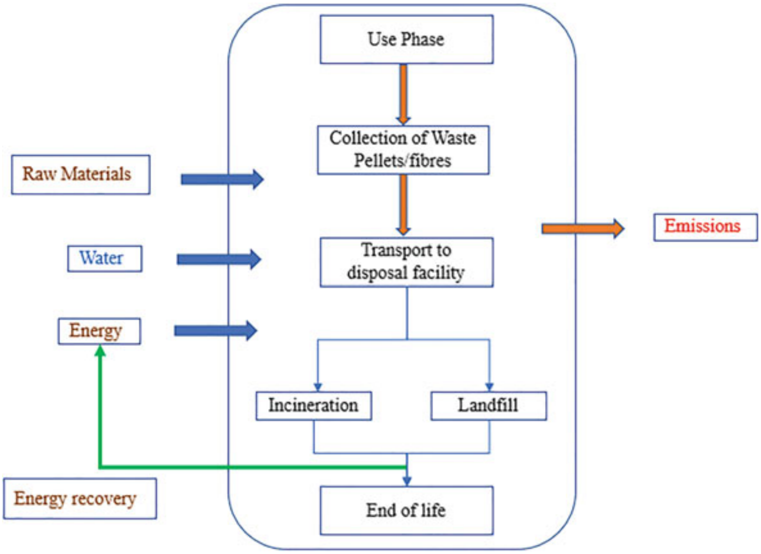


Fig. 5 System boundary for product end of life

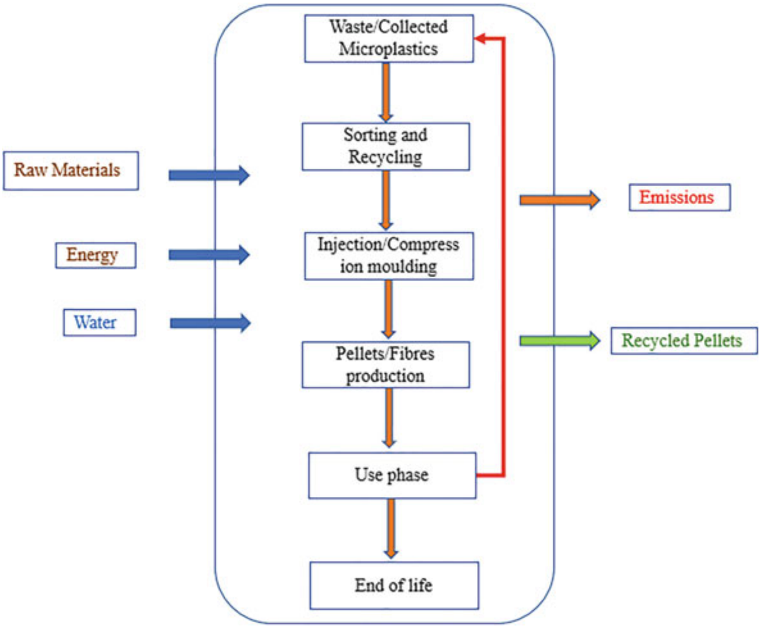


Fig. 6 System boundary for production of recycled microplastics

Chemical Recycling

Collection and sorting: It is a process in which all the waste plastics is collected and sorted from other mixed waste.

Depolymerisation: In this process, the polymer bonds are broken and are converted into monomers.

Polymerisation: In polymerisation process, the shredded plastic waste is melted by supplying heat/steam to produce recycled plastic resin.

1.7.2 Landfill

Approximately 7,500,000 tonnes of plastic waste were estimated to have been disposed of in landfills in Europe in the year 2016 [43]. This waste represents a significant opportunity for resource recovery via enhanced landfill mining, in line with recent circular economy initiatives [6]. In this chapter, it was recommended not to send the waste plastics into the landfill, as most of the plastic waste generated sent to landfill disposal will have more impacts than recycling and reuse of the same [30]. The plastic waste sent to landfill site will cause ingestion and entanglement into the animals which is used to collect food from it and ultimately causes death [16]. Hence, it is recommended that the waste generated can be sent for recycling as the best possible way to reduce the environmental burden.

1.7.3 Incineration

Plastic waste generated is sent to incineration might have some energy recovery benefits, which can be possible only when the incineration plant has a closed energy recovery facility in it [44]. It's highly not recommended to burn or pyrolysis waste plastics until it has a better recovery framework. Pyrolysis of waste plastics obtain many by-products such as oil and gas which has a better caloric value [9]. The waste incineration of plastics releases many toxic gases along with dioxins and ash. These toxic gases pollute atmospheric air and cause air pollution, which ultimately affects humans and animals.

Future Scope

The future scope of this chapter mainly talks about the following areas

1. Reduction in the microfibres usage from the primary microplastics in the various home appliances such as filters, cleaning equipments and garments such as towels.
2. It's always recommended to reduce the number of washes of garments, which directly reduces the release of secondary microplastics such as microfibres into the environment.

3. In this chapter, the procedure for LCA of microfibres is comprehensively explained and still there is lot of scope to conduct LCA by collecting some industrial primary data, which might be helpful to show the impacts on environment due to the use/release of microfibres.
4. It would be a better invention if any other natural/sustainable material replaces these microfibres, which can differentiate a big in the area of LCA and sustainable textile sector.

2 Conclusion

Use of plastics in our daily life is very common, and the people are transformed from no plastics era to a day that cannot start without plastics era. As the plastics are cheaper in cost and its lighter weight, it attracts many people to adapt these in their daily life but people forgot the environmental burden caused by these plastics. In this chapter, the use of plastics and production of microfibres are clearly shown along with their life cycle. This chapter shows the use of primary microfibres and release of secondary microfibres in our daily life as it has huge impact on environment and a potential area of research to create awareness on its life cycle. The plastic life cycle cannot be understood without the use of LCA tool, which is a diplomatic tool used to estimate the environmental burden of various products used in our daily life. Only LCA can be used to differentiate the products pros and cons to the people and environment, and making people to think about the sustainability and material resources. Among all the materials used by human in their daily life, plastics has got the highest % of use and at this stage people must be aware of its environmental impacts on other systems such as air, soil and water. Hence, this chapter initiated to show the LCA of microfibres and its environmental burden in a theoretical level. Also, the future scope clearly explains the potential research hidden in this area which would really help us to reduce the use of these plastics. Also, this chapter concludes that the increase in the use of cheap and highly available plastics causes huge environmental burden to the earth and it really need to find alternative materials to replace these carbon positive materials.

References

1. Alsabri A, Tahir F, Al-Ghamdi SG (2021) Life-cycle assessment of polypropylene production in the gulf cooperation council (Gcc) region. Polymers 13(21). https://doi.org/10.3390/polym13213793
2. Bahramian M, Yetilmezsoy K (2020) Life cycle assessment of the building industry: an overview of two decades of research (1995–2018). Energy Build 219:109917. https://doi.org/10.1016/j.enbuild.2020.109917

3. Barcelo D, Pico Y (2020) Case studies of macro- and microplastics pollution in coastal waters and rivers: is there a solution with new removal technologies and policy actions? Case Stud Chem Environ Eng 2:100019. https://doi.org/10.1016/j.cscee.2020.100019
4. Bui XT, Vo TDH, Nguyen PT, Nguyen VT, Dao TS, Nguyen PD (2020) Microplastics pollution in wastewater: characteristics, occurrence and removal technologies. Environ Technol Innov 19:101013. https://doi.org/10.1016/j.eti.2020.101013
5. Cai Y, Mitrano DM, Heuberger M, Hufenus R, Nowack B (2020) The origin of microplastic fiber in polyester textiles: the textile production process matters. J Clean Prod. https://doi.org/10.1016/j.jclepro.2020.121970
6. Canopoli L, Fidalgo B, Coulon F, Wagland ST (2018) Physico-chemical properties of excavated plastic from landfill mining and current recycling routes. Waste Manage 76:55–67. https://doi.org/10.1016/j.wasman.2018.03.043
7. Dalberg Advisors, de Wit W, Bigaud N (2019) No plastic in nature: assessing plastic ingestion from nature to people (an analysis for WWF). World Wide Fund For Nat 7
8. Daniel DB, Ashraf PM, Thomas SN (2020) Abundance, characteristics and seasonal variation of microplastics in Indian white shrimps (Fenneropenaeus indicus) from coastal waters off Cochin, Kerala, India. Sci Total Environ 737:139839. https://doi.org/10.1016/j.scitotenv.2020.139839
9. Fischer M, Scholz-Böttcher BM (2017) Simultaneous trace identification and quantification of common types of microplastics in environmental samples by pyrolysis-gas chromatography-mass spectrometry. Environ Sci Technol 51(9):5052–5060. https://doi.org/10.1021/acs.est.6b06362
10. Freeman S, Booth AM, Sabbah I, Tiller R, Dierking J, Klun K, Rotter A, Ben-David E, Javidpour J, Angel DL (2020) Between source and sea: the role of wastewater treatment in reducing marine microplastics. J Environ Manage 266:110642. https://doi.org/10.1016/j.jenvman.2020.110642
11. Fu Z, Wang J (2019) Current practices and future perspectives of microplastic pollution in freshwater ecosystems in China. Sci Total Environ 691:697–712. https://doi.org/10.1016/j.scitotenv.2019.07.167
12. Gileno LA, Turci LFR (2021) Life cycle assessment for PET-bottle recycling in Brazil: B2B and B2F routes. Cleaner Environ Syst. https://doi.org/10.1016/j.cesys.2021.100057
13. Goedkoop M, Oele M, Leijting J, Ponsioen T, Meijer E (2016) Introduction to LCA with SimaPro Colophon. Introduction to LCA with SimaPro
14. Gu Y, Wang H, Xu J, Wang Y, Wang X, Robinson ZP, Li F, Wu J, Tan J, Zhi X (2019) Quantification of interlinked environmental footprints on a sustainable university campus: a nexus analysis perspective. Appl Energy 246:65–76. https://doi.org/10.1016/j.apenergy.2019.04.015
15. Horowitz N, Frago J, Mu D (2018) Life cycle assessment of bottled water: a case study of Green2O products. Waste Manage 76:734–743. https://doi.org/10.1016/j.wasman.2018.02.043
16. Jagadeesh N, Sundaram B (2021) Journal of environmental chemical engineering a review of microplastics in wastewater, their persistence, interaction, and fate. 9
17. Jeyasanta KI, Sathish N, Patterson J, Edward JKP (2020) Macro-, meso- and microplastic debris in the beaches of Tuticorin district, Southeast coast of India. Mar Pollut Bull 154:111055. https://doi.org/10.1016/j.marpolbul.2020.111055
18. Karuppasamy PK, Ravi A, Vasudevan L, Elangovan MP, Dyana Mary P, Vincent SGT, Palanisami T (2020) Baseline survey of micro and mesoplastics in the gastro-intestinal tract of commercial fish from Southeast coast of the Bay of Bengal. Marine Pollut Bull 153:110974. https://doi.org/10.1016/j.marpolbul.2020.110974
19. Lares M, Ncibi MC, Sillanpää M, Sillanpää M (2018) Occurrence, identification and removal of microplastic particles and fibers in conventional activated sludge process and advanced MBR technology. Water Res 133:236–246. https://doi.org/10.1016/j.watres.2018.01.049
20. Le KN, Tran CNN, Tam VWY (2018) Life-cycle greenhouse-gas emissions assessment: an Australian commercial building perspective. J Clean Prod 199:236–247. https://doi.org/10.1016/j.jclepro.2018.07.172

21. Monteiro H, Freire F (2012) Life-cycle assessment of a house with alternative exterior walls: comparison of three impact assessment methods. Energy Build 47:572–583. https://doi.org/10.1016/j.enbuild.2011.12.032
22. Muthu SS, Li Y, Hu JY, Mok PY (2011) Carbon footprint of shopping (grocery) bags in China, Hong Kong and India. Atmosp Environ 45(2):469–475. https://doi.org/10.1016/j.atmosenv.2010.09.054
23. Nagireddi J, Santhosh, Gedela K, Mahabu, Shaik S, Sundaram B (2022) Environmental performance and cost assessment of precast structural elements for cleaner construction solutions: LCA approach. J Hazard Toxic Radioactive Waste 26(2):04021052. https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000667
24. Naidu SA (2019) Preliminary study and first evidence of presence of microplastics and colorants in green mussel, *Perna viridis* (Linnaeus, 1758), from southeast coast of India. Mar Pollut Bull 140:416–422. https://doi.org/10.1016/j.marpolbul.2019.01.024
25. Narmadha VV, Jose J, Patil S, Farooqui MO, Srimuruganandam B, Saravanadevi S, Krishnamurthi K (2020) Assessment of microplastics in roadside suspended dust from urban and rural environment of Nagpur, India. Int J Environ Res 14(6):629–640. https://doi.org/10.1007/s41742-020-00283-0
26. Padervand M, Lichtfouse E, Robert D, Wang C (2020) Removal of microplastics from the environment. A review. Environ Chem Lett 18(3):807–828. https://doi.org/10.1007/s10311-020-00983-1
27. Palacios-Mateo C, van der Meer Y, Seide G (2021) Analysis of the polyester clothing value chain to identify key intervention points for sustainability. In: Environmental sciences Europe, vol 33, issue 1. Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1186/s12302-020-00447-x
28. Ragaert K, Delva L, van Geem K (2017) Mechanical and chemical recycling of solid plastic waste. In: Waste management, vol 69. Elsevier Ltd, pp 24–58. https://doi.org/10.1016/j.wasman.2017.07.044
29. Ramesh M, Deepa C, Kumar LR, Sanjay MR, Siengchin S (2022) Life-cycle and environmental impact assessments on processing of plant fibres and its bio-composites: a critical review. J Ind Text 51(4):5518S-5542S. https://doi.org/10.1177/1528083720924730
30. Rena AS, Chavan D, Aiman S, Kumar S (2020) Reducing greenhouse gas emission from waste landfill. Encycl Renew Sustain Mater 685–701. https://doi.org/10.1016/b978-0-12-803581-8.11022-7
31. Rogers KL, Carreres-Calabuig JA, Gorokhova E, Posth NR (2020) Micro-by-micro interactions: how microorganisms influence the fate of marine microplastics. Limnol Oceanogr Lett 5(1):18–36. https://doi.org/10.1002/lol2.10136
32. Shen L, Worrell E, Patel MK (2010) Open-loop recycling: a LCA case study of PET bottle-to-fibre recycling. Resour Conserv Recycl 55(1):34–52. https://doi.org/10.1016/j.resconrec.2010.06.014
33. Shen M, Song B, Zhu Y, Zeng G, Zhang Y, Yang Y, Wen X, Chen M, Yi H (2020) Removal of microplastics via drinking water treatment: current knowledge and future directions. Chemosphere 251:126612. https://doi.org/10.1016/j.chemosphere.2020.126612
34. Subramanian K, Chopra SS, Cakin E, Li X, Lin CSK (2020) Environmental life cycle assessment of textile bio-recycling—valorizing cotton-polyester textile waste to pet fiber and glucose syrup. Resour Conserv Recycl. https://doi.org/10.1016/j.resconrec.2020.104989
35. Sun J, Dai X, Wang Q, van Loosdrecht MCM, Ni BJ (2019) Microplastics in wastewater treatment plants: detection, occurrence and removal. Water Res 152:21–37. https://doi.org/10.1016/j.watres.2018.12.050
36. Talvitie J, Mikola A, Koistinen A, Setälä O (2017) Solutions to microplastic pollution—removal of microplastics from wastewater effluent with advanced wastewater treatment technologies. Water Res 123:401–407. https://doi.org/10.1016/j.watres.2017.07.005
37. Tiwari M, Rathod TD, Ajmal PY, Bhangare RC, Sahu SK (2019) Distribution and characterization of microplastics in beach sand from three different Indian coastal environments. Mar Pollut Bull 140:262–273. https://doi.org/10.1016/j.marpolbul.2019.01.055

38. Van der Harst E, Potting J (2014) Variation in LCA results for disposable polystyrene beverage cups due to multiple data sets and modelling choices. Environ Model Softw 51:123–135. https://doi.org/10.1016/j.envsoft.2013.09.014
39. Veerasingam S, Ranjani M, Venkatachalapathy R, Bagaev A, Mukhanov V, Litvinyuk D, Verzhevskaia L, Guganathan L, Vethamony P (2020) Microplastics in different environmental compartments in India: analytical methods, distribution, associated contaminants and research needs. TrAC—Trends Anal Chem 133:116071. https://doi.org/10.1016/j.trac.2020.116071
40. Westphalen H, Abdelrasoul A (2018) Challenges and treatment of microplastics in water. Water Challenges Urbanizing World. https://doi.org/10.5772/intechopen.71494
41. Wu M, Tang W, Wu S, Liu H, Yang C (2021) Fate and effects of microplastics in wastewater treatment processes. Sci Total Environ 757:143902. https://doi.org/10.1016/j.scitotenv.2020.143902
42. Xu S, Ma J, Ji R, Pan K, Miao AJ (2020) Microplastics in aquatic environments: occurrence, accumulation, and biological effects. Sci Total Environ 703:134699. https://doi.org/10.1016/j.scitotenv.2019.134699
43. Yadav V, Sherly MA, Ranjan P, Tinoco RO, Boldrin A, Damgaard A, Laurent A (2020) Framework for quantifying environmental losses of plastics from landfills. Resour Conserv Recycl 161:104914. https://doi.org/10.1016/j.resconrec.2020.104914
44. Zhou J, Liu G, Wang S, Zhang H, Xu F (2020) TG-FTIR and Py-GC/MS study of the pyrolysis mechanism and composition of volatiles from flash pyrolysis of PVC. J Energy Inst 93(6):2362–2370. https://doi.org/10.1016/j.joei.2020.07.009
45. Ziajahromi S, Neale PA, Leusch FDL (2016) Wastewater treatment plant effluent as a source of microplastics: review of the fate, chemical interactions and potential risks to aquatic organisms. Water Sci Technol 74(10):2253–2269. https://doi.org/10.2166/wst.2016.414

Life Cycle Assessment Approach to Denim Dyeing: Denim Dyeing with Natural Dyes

Selin Hanife Eryürük, Gülay Özcan, and Pelin Altay

Abstract Nowadays, environmental protection and sustainability efforts are increasing to reduce environmental damage, especially considering denim production. The use of synthetic-based products in raw materials, dyes, and mordants in denim dyeing causes several environmental pollution problems. This study aims to identify the issues that affect the sustainability of denim throughout its life cycle and to provide an environmentally friendly denim dyeing method. Turkish organic cotton fabric was used as a raw material for denim production. In order to achieve a blue denim color shade, samples were dyed with two different natural dyes (Isatis tinctoria and red cabbage) in the presence of different mordants and different pH regulators. Tannic acid was used as an environmentally friendly alternative to metal mordants. Organic indigo dye was used to obtain the reference dyed sample for comparison. The experimental results show that blue denim color can be obtained with the use of natural dyes, Isatis tinctoria and red cabbage, under optimized conditions in the presence of appropriate mordant. Natural mordant, tannic acid, gave blue denim color with Isatis tinctoria under optimized process conditions. Subsequent post-treatment processes should be applied to dyed samples to improve color fastness properties. It is expected that this study provides alternative perspectives to denim dyeing through a more sustainable approach.

Keywords LCA assessment of denim · Ecofriendly denim dyeing · Natural dyes · Isatis tinctoria · Red cabbage · Tannic acid

S. H. Eryürük (✉) · G. Özcan · P. Altay
Textile Engineering Department, Textile Technologies and Design Faculty, Istanbul Technical University, Istanbul, Turkey 34437
e-mail: eryuruk@itu.edu.tr

G. Özcan
e-mail: ozcangul@itu.edu.tr

P. Altay
e-mail: pelinaltay@itu.edu.tr

S. S. Muthu (ed.), *Progress on Life Cycle Assessment in Textiles and Clothing*, Textile Science and Clothing Technology,
https://doi.org/10.1007/978-981-19-9634-4_11

1 Introduction

Denim fabrics, which are preferred by all genders, age groups, and professions, have an important share among the fabrics produced today. Denim is a significant part of the fashion industry, and the popularity of denim fabrics is mainly due to the attractiveness of the blue color and the different effects that occur after repeated washing. Denim fabrics, which were firstly used in 1853, were produced from indigo-dyed yarns as warp and not dyed as weft. Denim fabric, originally produced from hemp, has recently been produced with 100% cotton or a polyester-cotton blend. Denim fabrics are heavily involved in the textile sector in Turkey and in other countries around the world. Denim fabrics are frequently used in products such as shirts, t-shirts, skirts, bags, wallets, jackets, coats as well as jeans. With special stretch jeans, natural jeans, and recycled denim, developments in denim are growing, and denim apparel production and demand for denim in the global market are increasing day by day [1, 2].

As the demand for the denim industry has been increasing in the world, the environmental damage associated with denim jean production is also increasing. In the denim industry, large quantities of cotton, immense amount of water, and toxic chemicals are consumed resulting in environmental damage to rivers, ecosystems, and communities. In order to improve the sustainability of the denim industry, the environmental impact of denim products during production, use, and disposal should be evaluated from a life cycle perspective. The life cycle assessment (LCA) of denim focuses on the key environmental impacts throughout all its stages (raw material, resources consumed, production methods, waste management, etc.), from fiber to denim retailing.

The demand for sustainable denim production depends on the awareness of these environmental issues among companies, organizations, and consumers and an understanding of the issues that affect sustainability at each stage over its life cycle. Denim production consists of raw material selection, indigo dyeing, sizing, weaving, finishing, and washing processes, creating an ecological problem due to the carbon footprint, water footprint, waste, and the chemicals used [3–6]. It is estimated that the total denim consumption is over 2.1 million metric tons, and 38.5 trillion litres of water is consumed per year. It has been reported that the contribution of denim production to total global greenhouse gas emissions is approximately 0.3–1% and increases with the presence of workers working for transportation and cotton production. Besides, the use of indigo and cotton, which is consumed about 5226 kg annually, poses serious ecological problems for denim production stages. According to Levi's life cycle assessment, 33.2 kg of carbon dioxide emissions, 3480 L of water, and 400.1 mega joules of energy are consumed in the production of denim jeans with conventional methods [7–9].

While designing an environmentally friendly denim process toward a circular economy strategy, there are some key issues to be considered such as using less harmful chemicals, reducing water and energy consumption, reducing carbon footprint and water footprint, and efficient use of resources, leading to a low amount of waste, and being as sustainable as possible. Furthermore, while these constraints are considered, another important issue is the performance and mechanical properties of denim fabrics, which should meet customer expectations such as tensile strength, color fastness, and dyeing efficiency in an economically viable way.

Denim production with an environmentally friendly approach can be summarized under four main topics (Fig. 1). The first issue in ecofriendly denim production is the selection of the raw material including the selection of fiber (organic cotton, recycled cotton, and better cotton), selection of dyestuff (organic indigo, and other natural dyes such as quince peel, galangal, hibiscus, and red cabbage), and selection of mordants (natural mordants instead of metallic mordants). Denim fabric is mostly produced from 100% cotton yarn. Organic cotton textile production in Turkey has high productivity for organic cotton farming, and white cotton fibers have higher fiber strength than natural colored cotton fibers. The use of white and naturally colored organic cotton has proven to be a promising method to increase the sustainability of textile production [10]. Organic mordants can be used instead of inorganic mordants to reduce the environmental impact because it is easier to remove and degrade organic mordants. Baig et al. studied the dyeing of cotton fabric with reactive dyes in the presence of three different organic mordants (sodium citrate, potassium acetate, and ammonium acetate). It was concluded that cotton fabrics dyed with organic mordants and inorganic mordants had comparable durability properties, and sodium citrate showed better durability than other salts [11].

The second most important issue for ecological denim production is the selection of environmentally friendly methods for both dyeing and finishing and the determination of optimum process conditions for improving the product performance, with the aim of efficient use of resources. Ecological denim dyeing consists of the selection of natural based dyestuffs and the determination of optimum process conditions

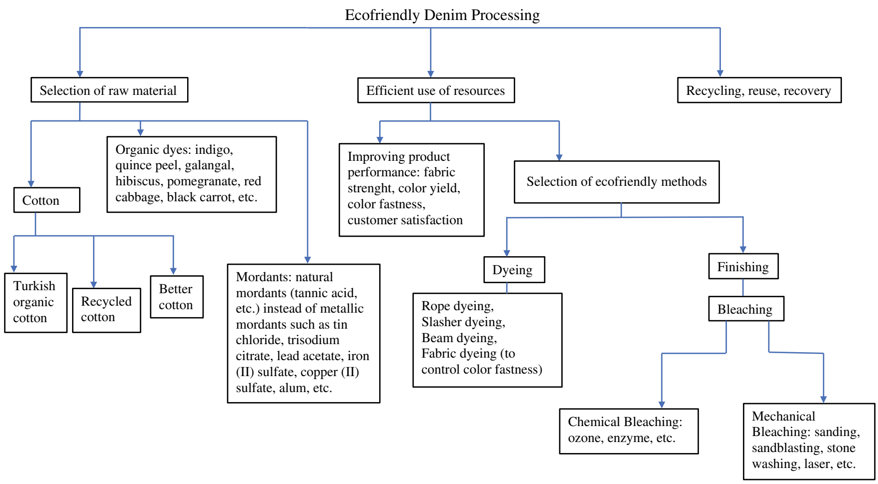


Fig. 1 Denim production with an environmentally friendly approach

to provide coloration with acceptable color fastness properties. Synthetic indigo dye, mostly sulfur-based, is used in denim dyeing, and it seriously affects the health of the workers in the production step. Synthetic indigo dyestuffs in the dyeing process are harmful to the environment as they cause high biochemical oxygen demand (BOD), chemical oxygen demand (COD), dissolved solids (TDS), and total suspended solids (TSS) in the wastewater discharged from dyeing. These dye residues are relatively stable to light and heat and resistant to biodegradation, making them difficult to remove from wastewater. In order to overcome these problems, natural based dyes (pomegranate, hibiscus, quince peel, red cabbage, black corrot, etc.), which have many advantages over synthetic dyes due to their ecological, non-toxic, and non-carcinogenic properties, can be used in denim dyeing and as a result, carbon footprint level can be minimized [8, 12–18].

In the denim fabric production process, the finishing processes applied after the dyeing process are of great importance in terms of the comfort and aesthetic properties of the product. In addition to special color effects, aged, faded, and wash-down effects are provided by finishing processes. There are several methods for the wash-down finishing effect, which is the decolorization of indigo. Stone washing is a traditional finishing method, which gives an aged and worn-out feature to denim. In this method, in which pumice stone is generally used as an abrasive in the washing cycle, water, chemical, and energy consumption is quite high and the process can take up to 6 h [19]. The most known wet finishing method for denim is bleaching with chemicals such as sodium hypochlorite, calcium hypochlorite, hydrogen peroxide, and potassium permanganate [20]. Ozone and enzyme usage may be used as alternative ecofriendly methods to bleaching with chemicals. Ozone requires less rinse washing and therefore consumes less water. The remaining ozone at the end of the process can be converted into oxygen and water and, its residues do not pollute the environment. However, ozone bleaching has a disadvantage that it requires excessive investment [21]. Enzyme is another good alternative to the strong chemicals used in bleaching and does not harm the fabric in terms of fabric quality, strength, and elasticity. For a long time to achieve the whisker effect, the potassium permanganate (PP) spray method has been used to lighten some specific areas on denim and create the effect. This method is labor-intensive and can cause skin irritation, burns, or short- and long-term diseases with prolonged exposure without proper equipment [22]. Another method for using the whisker effect is laser application, which is an alternative environmentally friendly and sustainable dry finishing technique that does not require labor, uses less water, and saves chemicals and energy. In addition to the whisker effect, the laser can give a vintage effect, patterns, patches, intentional holes, and tears. Choudhury et al. reported that laser has been used instead of harmful methods such as hand sanding, sandblasting, grinding, and others [23–27].

Denim product performance depends on several parameters including raw material used, fabric structure, processing of denim fabric such as weaving, dyeing, finishing, cutting, and sewing, etc. In both dyeing and finishing processes, optimization of process parameters is required for efficient use of limited resources. Improving product performance such as tensile strength, tear strength, color yield, and colorfastness is essential to achieve long-term profitability and customer satisfaction [2, 10, 20–22]. Lastly, the fourth issue for ecological denim production is recycle/reuse/recovery in creating sustainable waste management to minimize waste and contribute to sustainability [28].

This study mainly focuses on ecofriendly denim dyeing toward the life cycle assessment approach. Dyeing is the most polluting and energy-intensive process in the life cycle of textiles. Denim dyeing is one of the most water-consuming processes and the top source of pollution in the world. Many studies have been carried out to reduce the adverse ecological effects of the dyeing process. In this study, it is aimed to conduct a denim dyeing process with natural dyes (organic indigo, Isatis tinctoria, and red cabbage) in order to reduce the overall environmental impact throughout the entire life cycle of the product. 100% organic Turkish cotton was used to reduce the environmental effect to provide efficient use of resources in a circular economy and to decrease dependence on foreign resources. Iron (II) sulfate and copper sulfate (CuSO4) as metallic mordants and tannic acid, as a natural mordant, were chosen because of their superior priorities over others [13, 29–32]. Tannin is a natural mordant substance found in almost all parts of a plant including roots, stems, bark, leaves, and fruits. High color fastness values are obtained with tannin in natural dyes [30]. 100% organic Turkish cotton was dyed with natural dyes in the presence of the most convenient mordants to establish an indigo blue color on the denim, considering environmental issues.

2 Experimental

2.1 Material

As the first step of ecofriendly denim processing, woven denim fabric made of 100% organic Turkish cotton was provided. Isatis tinctoria, one of the natural dyestuffs, and red cabbage were chosen to dye denim fabric, while organic indigo was used for reference dyed samples.

In the dyeing process, four different mordants, namely tannic acid, iron (II) sulfate, copper (II) sulfate, and sodium hydrosulfite, were used as mordants for better dye uptake to the fibers, and three different pH regulators, namely sodium carbonate, sodium hydroxide, and ammonia, were used to adjust the pH of the dyebath.

Table 1 Type of chemicals used in this study

Dyestuff	Mordant	pH regulator
Organic indigo	Tannic Acid	Sodium carbonate
Isatis tinctoria	Iron (II) sulfate	Sodium hydroxide
Red cabbage	Copper sulfate	Ammonia
	Sodium hydrosulfite	

2.2 Methods

2.2.1 Pre-washing Process

Before the dyeing process, denim samples were washed using a Gyrowash device with a non-ionic wetting agent at a liquor ratio of 1:30 at 60 °C for 30 min. This process was carried out for removing the sizing agent from the raw fabric for better adhesion of the dyestuffs to the fabric.

2.2.2 Dyeing Process

In this study, organic cotton fabric was dyed with organic indigo to obtain an indigo-dyed reference sample. Two types of natural dyestuffs (Isatis tinctoria and red cabbage), 4 types of mordants (tannic acid, iron (II) sulfate, copper sulfate, and sodium hydrosulfite), and 3 types of pH regulators (sodium carbonate, sodium hydroxide, and ammonia) were used to achieve indigo blue color, and the results were compared with indigo dyed samples. Sodium carbonate, sodium hydroxide, and ammonia were used as pH regulators to adjust the pH to around 10. The dyestuffs, mordants, and pH regulators used in this study are given in Table 1.

2.3 Dyeing with Organic Indigo (Reference Dyed Sample)

Organic cotton fabric was dyed with organic indigo as a reference dyed sample according to the exhaustion method. Organic indigo and hydrosulfite were used to prepare the dyeing solution. The pH was adjusted to 10 using a NaOH solution. Dyeing was conducted in a dyeing machine at 40 °C for 30 min at a liquor ratio of 1:50.

Table 2 Dyeing of organic cotton fabric with different natural dyestuffs in the presence of different mordants and pH regulators

Natural Dyestuff	Dyeing method	Mordant	pH regulator
Organic indigo (reference dyeing)	Exhaustion	Sodium hydrosulfite	Sodium hydroxide
Isatis tinctoria	Exhaustion	–	Sodium carbonate
Isatis tinctoria	Exhaustion	–	Sodium hydroxide
Isatis tinctoria	Exhaustion	–	Ammonia
Isatis tinctoria	Exhaustion	Tannic acid	–
Isatis tinctoria	Exhaustion	Iron (II) sulfate	–
Isatis tinctoria	Exhaustion	Copper (II) sulfate	–
Isatis tinctoria	Exhaustion	Sodium hydrosulfite	–
Red cabbage	Exhaustion and padding method	–	Sodium carbonate
Red cabbage	Exhaustion and padding method	–	Sodium hydroxide
Red cabbage	Exhaustion and padding method	–	Ammonia
Red cabbage	Exhaustion and padding method	Tannic acid	Sodium carbonate
Red cabbage	Exhaustion and padding method	Iron (II) sulfate	Sodium carbonate
Red cabbage	Exhaustion and padding method	Copper (II) sulfate	Sodium carbonate
Red cabbage	Exhaustion and padding method	Sodium hydrosulfite	Sodium carbonate

2.4 *Dyeing with Isatis tinctoria*

Fabric samples were dyed with Isatis tinctoria at a ratio of 1:1 dyestuff/fabric, 1:50 liquor ratio, and 90 °C for 30 min. Dyeing was done using different pH regulators to adjust the pH to around 10, and using different mordants without pH regulators (Table 2).

2.5 *Dyeing with Red Cabbage*

A red cabbage stock dye solution was prepared by boiling 200 g of red cabbage in 750 mL of water for 30 min. The dyeing with red cabbage was done according to two different methods, exhaustion and padding methods. The dyeing by exhaustion method was performed at 80 °C for 30 min at a liquor ratio of 1:50, while the dyeing by padding method was carried out at room temperature for 12 h. Dyeing was carried out using different pH regulators in the absence of a mordant and using sodium carbonate in the presence of different mordants (Table 2).

2.6 Color Measurement

Color measurements of the dyed samples were done using a Datacolor 650™ spectrophotometer. CIE L*a*b coordinates: a* represents the red/green value; b* the yellow/blue value. The CIE L*C*H° color model uses the same XYZ-derived color space as L*a*b*, but uses the cylindrical coordinates of lightness, chroma, and hue angle instead of colors. The K/S value indicates the depth of the surface of the dyed fabric. Delta E is the total distance or difference between two colors [33].

2.7 Color Fastness Tests

Color fastness to washing, color fastness to artificial light, and color fastness to rubbing were tested according to the related standards, TS EN ISO 105-C06, TS EN ISO 105-B02, and TS EN ISO 105-X12, respectively.

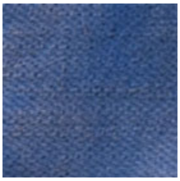
3 Results and Discussion

Among the dyeing experiments in Table 2, dyeings in which the blue shade was obtained are given in Table 3. As can be seen from Table 3, the highest K/S value of 4.27 was obtained with the reference organic indigo-dyed sample. Depending on the mordant used, all samples have different color shades (more greenish or more reddish) with different color yields (K/S value). Samples dyed with red cabbage have the highest L* value, indicating that they have the lightest color shade compared to the others. The reference dyed sample has a more greenish shade, while all other samples have more reddish shades. b* value of the batch samples is close to yellow, while the b* value of the reference dyed sample is close to the blue color.

3.1 Color Fastness Test Results

Color fastness to washing test results is given in Table 4. It is seen that all samples have low grayscale ratings for change in color. However, samples dyed with Isatis tinctoria in the presence of iron (II) sulfate, copper (II) sulfate, and hydrosulfite have grayscale ratings for staining in the range of 3/4–4, which is similar to the organic indigo-dyed sample. In addition, using ammonia as a mordant was found to have

Table 3 Dyeings in which blue shade was obtained

Dyeing	Dyed samples
Organic indigo	
Isatis tinctoria + Sodium carbonate	
Isatis tinctoria + Sodium hydroxide	
Isatis tinctoria + Ammonia	
Isatis tinctoria + Tannic acid	

(continued)

a negative effect on the colorfastness to washing. Dyed samples with red cabbage have the highest grayscale ratings for staining (4/5), indicating that there are no perceived color differences with the untreated sample. As can be seen from the color fastness results to artificial daylight in Table 5, red cabbage dyeings have the lowest grayscale ratings (1–1/2), meaning that they have very poor color fastness against artificial daylight.

While all of the Isatis tinctoria -dyed samples have very poor rubbing properties, samples dyed with red cabbage have the highest rubbing fastness value in the grayscale rating range of 4/5.

Table 3 (continued)

Dyeing	Dyed samples
Isatis tinctoria + Iron (II) sulfate	
Isatis tinctoria + Copper (II) sulfate	
Isatis tinctoria + Sodium hydrosulfite	
Red cabbage + Iron (II) sulfate (padding method)	
Red cabbage + Copper (II) sulfate (padding method)	

4 Conclusion and Future Perspective

The creation of a pair of jeans requires a huge amount of water, which includes cotton cultivation, dyeing, and finishing procedures. A significant quantity of energy is expended for all activities, including cotton irrigation and downstream processing such as spinning, weaving, and sewing. The use of synthetic products such as raw materials, the presence of harmful chemicals in cotton production, excessive water consumption, chemicals in dyeing and finishing processes, dyestuff wastes, and wastes generated during finishing processes all contribute to environmental pollution and prevent sustainable denim production. From this point of view, this study aims

Table 4 Test results of color fastness to washing

Dyed samples	Color fastness to washing						
	Change in color	Staining					
		Wool	Polyester	Polyamide	Polyacrylic	Cotton	Acetate
Organic indigo	2	4	3/4	4	4	4	4
Isatis tinctoria + Sodium carbonate	2	2/3	2/3	2/3	2/3	2/3	4
Isatis tinctoria + Sodium hydroxide	1/2	3	3	3	3	2/3	3
Isatis tinctoria + Ammonia	2	2	2	2	2	2	3
Isatis tinctoria + Tannic acid	2	3	3	3	3	2/3	4/5
Isatis tinctoria + Iron (II) sulfate	2	4	4	4	4	3/4	4/5
Isatis tinctoria + Copper (II) sulfate	1/2	4	4	4	4	3/4	4
Isatis tinctoria + Sodium hydrosulfite	1/2	4	4	4	4	3/4	4
Red cabbage + Iron (II) sulfate (padding method)	1	4/5	4/5	4/5	4/5	4/5	4/5
Red cabbage + Copper (II) sulfate (padding method)	1	4/5	4/5	4/5	4/5	4/5	4/5

to provide more sustainable and environmentally friendly improvements in denim production methods by considering environmental issues such as water use, energy consumption, chemical consumption, and environmental pollution.

In this study, an ecofriendly denim dyeing process was conducted with the use of 100% organic cotton fabric and natural dyes (organic indigo, Isatis tinctoria, and red cabbage) in the presence of different mordants and pH regulators to obtain blue denim color. The use of red cabbage in dyeing has decreased the negative impacts on the environment. Samples dyed with red cabbage by padding method gave a blue color without heating the dyebath solution, therefore providing energy saving and reduced greenhouse gas production. However, the samples dyed with

Table 5 Test results of color fastness to artificial daylight

Dyed samples	Color fastness to artificial daylight
Organic indigo	4/5
Isatis tinctoria + Sodium carbonate	4/5
Isatis tinctoria + Sodium hydroxide	4
Isatis tinctoria + Ammonia	4/5
Isatis tinctoria + Tannic acid	4
Isatis tinctoria + Iron (II) sulfate	4/5
Isatis tinctoria + Copper (II) sulfate	4/5
Isatis tinctoria + Sodium hydrosulfite	4/5
Red cabbage + Iron (II) sulfate (padding method)	1/2
Red cabbage + Copper (II) sulfate (padding method)	1

Isatis tinctoria gave more successful color retention than the samples dyed with red cabbage. In order to improve the color fastness values, a suitable post-treatment process should be applied to dyed samples. Isatis tinctoria can be used with tannic acid, an environmentally friendly alternative to metal mordants, to obtain blue color, and color fastness properties can be improved by the post-treatment process.

Future studies will focus on achieving reproducible dyeings in blue denim shades with high dyeing efficiency and desired color fastness properties using different natural dyes. In the next step, denim faded effects with acceptable tensile strength values will be achieved by using laser technology, which is an ecological and sustainable method, to minimize water, chemical, and energy consumption in the denim bleaching process.

Acknowledgements The authors would like to thank Başak Aslanpay, Ezgi Hırca, Hande Bulut, and Perihan Yılmaz for their assistance with conducting the experiments.

Conflict of interest/Competing interests The authors have no conflicts of interest to declare that are relevant to the content of this article.

References

1. Miller D, Woodward S (2011) Global denim. Des Cult 4(2):243–245. https://doi.org/10.2752/175470812X13281948975819
2. Annapoorani SG (2017) Introduction to denim. Sustainability in Denim. The Textile Institute Book Series. ISBN: 0081020449, 9780081020449
3. Moisander J, Markkula A, Eräranta K (2010) Construction of consumer choice in the market: challenges for environmental policy. Int J Consum Stud 34(1):73–79. https://doi.org/10.1111/j.1470-6431.2009.00821.x
4. Subramanian SM (ed) (2017) Sustainability in denim. Elsevier Publications, Cambridge. Chapter-2: Environmental impacts of denim, pp 27–47. https://doi.org/10.1016/B978-0-08-102043-2.00005-8
5. Fidan FŞ, Aydoğan EK, Uzal N (2021) An integrated life cycle assessment approach for denim fabric production using recycled cotton fibers and combined heat and power plant. J Cleaner Prod 287:125439. https://doi.org/10.1016/j.jclepro.2020.125439
6. Karthik T, Murugan R (2017) Carbon footprint in denim manufacturing. Sustainability in Denim. The Textile Institute Book Series. ISBN: 0081020449, 9780081020449. pp 111–125
7. Hedman EA (2018) Comparative life cycle assetments of jeans: a case study performed at nudie jeans. KTH, Sustainable development. Environmental science and Engineering
8. Rathinamoorthy R, Karthik T (2017) Chemicals and effluent treatment in denim processing. Sustainability in denim. The Textile Institute Book Series. ISBN: 0081020449, 9780081020449, pp 111–125
9. Unal F, Yavas A, Avınc O (2020) Sustainability in textile design with laser technology. In: Muthu SS, Gardetti MA (eds) sustainability in the textile and apparel industries, sustainable textiles, clothing dressing and repurposing. Springer, Switzerland
10. Günaydın G, Palamutçu S, Soydan A, Yavaş A, Avınc O, Demirtaş M (2019) Evaluation of fiber, yarn, and woven fabric properties of naturally colored and white Turkish organic cotton. J Textile Inst. https://doi.org/10.1080/00405000.2019.1702611
11. Baig R, Waqar A, Dilshad H, Rana H, Muhammad A, Ul-Haq N (2019) Eco-friendly route for dyeing of cotton fabric using three organic mordants in reactive dyes. Industria Textila (70)
12. Vadivel VK, Cikurel H, Mamane H (2021) Removal of indigo dye by $CaCO_3/Ca(OH)_2$ composites and resource recovery. Ind Eng Chem Res 60(28):10312–10318
13. Başaran F, Aydın Ş (2019) Nar (*Punica Granatum* L.) Bitkisinin Doğal Mordanlarla Boyama ve Haslık Değerleri. IBAD J Soc Sci 5:397–406. https://doi.org/10.21733/ibad.627223
14. Tölek Ş, Doba Kadem F (2016) An investigation on colour analysis and fastness properties of the denim fabric dyed with a different method. Tekstil ve Konfeksiyon 26:198–204
15. Vankar PS, Shukla D (2011) Natural Dyeing with Anthocyanins from Hibiscus Rosa sinensis Flowers. J Appl Polym Sci 122(5):1–8. https://doi.org/10.1002/app.34415
16. Ishaque F, Khatri A, Ali S, Gunejo N (2019) Indigenous natural indigo dye for denim industry. In: 2nd international conference on sustainable development in civil engineering, pp 506–510
17. Önal A, Subasar D (2012) Cotton, wool and linen fabrics dyeing with natural dye extracted from red cabbage (*Brassica oleracea* var. capitata f.rubra). Gaziosmanpaşa Bilimsel Araştırma Dergisi 1:35–41
18. Shukla D, Vankar PS (2013) Natural dyeing with black carrot: new source for newer shades on silk. J Nat Fibers 10(3):207–218. https://doi.org/10.1080/15440478.2012.757031
19. Samanta K, Basak S, ve Chattopadhyay S (2017) Environmentally friendly denim processing using water-free technologies. Muthu SS (eds) Sustainability in Denim. Woodhead Publishing, Cambridge
20. Periyasamy AP, Militky J (2017) Denim processing and health hazards. Sustainability in denim, p. 175. Woodhead Publishing. https://doi.org/10.1016/b978-0-08-102043-2.00007-1
21. Periyasamy AP, Ramamoorthy SK, Lavate SS (2019) Eco-friendly denim processing. In: Torres-Martinez LM, Kharissova OV, Kharisov BI (eds) Handbook of ecomaterials. Springer International Publishing, pp 1572–1576. https://doi.org/10.1007/978-3-319-48281-1

22. Kalaoğlu F, Paul R (2015) Finishing of jeans and quality control. In: Paul R (ed) Denim. Woodhead Publishing, pp 431–433. https://doi.org/10.1016/b978-0-85709-843-6.00014-7
23. Kan C (2014) CO_2 laser treatment as a clean process for treating denim fabric. J Cleaner Prod 624–631
24. Ondogan Z, Pamuk O, Ondogan E, Ozguney A (2004) Improving the appearance of all textile products from clothing to home textile using laser technology. Optics Laser Technol 631–637
25. Chow FYL, Chan A, Kan CW (2012) Effect of CO_2 laser irradiation on the properties of cotton fabric. Text Res J 1220–1234
26. Choudry AKR (2017) Environmental impacts of denim washing. Sustainability in denim. Woodhead Publishing, pp 49–81. https://doi.org/10.1016/b978-0-08-102043-2.00003-4
27. Hoque S, Rashid MA, Chowdhury S, Chakraborty A, Haque AN (2018) Alternative washing of cotton denim fabrics by natural agents. Am J Environ Protect 7(6):79–83.https://doi.org/10.11648/j.ajep.20180706.12
28. Radhakrishnan S (2017) Denim recycling. In: Muthu S (eds) Textiles and clothing sustainability. Textile science and clothing technology. Springer, Singapore. https://doi.org/10.1007/978-981-10-2146-6_3
29. Erdem İşmal Ö (2019) Doğal boya uygulamalarının değişen yüzü ve yenilikçi yaklaşımlar, YEDİ: Sanat, Tasarım ve Bilim Dergisi, Yaz 22:41–58
30. Merdan N, Eyüpoğlu Ş, Nayci Duman M (2017) Ecological and sustainable natural dyes. Text Clothing Sustain (1)
31. Prabu HG, Sundrarajan M (2006) Effect of the bio-salt trisodium citrate in the dyeing of cotton. 118(3):131–134. https://doi.org/10.1111/j.1478-4408.2002.tb00370.x
32. Kara Ö, Döğeroğlu T (n.d.) Bazı Özel Atlklarln İnsana Ve Dogaya Etkileri 1. Anatolia
33. Becerir B (2017) Color concept in textiles: a review. J Text Eng Fashion Technol 1(6):240–244. https://doi.org/10.15406/jteft.2017.01.00039