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Environmental Sustainability in the Fashion Industry: A Case Study on the Application of the OLCA Methodology

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ABSTRACT

This thesis investigates the state of environmental sustainability of the fashion industry, focusing on the assessment of corporate practices and the implementation of methodologies such as Life Cycle Assessment (LCA) and Organizational Life Cycle Assessment (OLCA). With the fashion industry being one of the most resource-intensive and polluting sectors globally, this study aims to highlight its significant environmental impacts and propose strategies for improvement.

A comprehensive literature review was conducted, examining global and regional policies, industry practices, and sustainability certifications. The research delves into the negative environmental effects of the fashion industry, including high water consumption, chemical pollution, greenhouse gas emissions, and waste generation. Specific attention is given to the rapid growth of fast fashion and its detrimental impact on environmental sustainability.

Using the OLCA methodology, a case study of an apparel manufacturing organization in Italy has been presented. The study evaluates the environmental performance of the company over a one-year period, utilizing the SimaPro LCA tool and the Ecoinvent database. The analysis includes a detailed inventory of inputs and outputs, covering direct and indirect activities, and assesses the environmental impacts of said organization across multiple impact categories such as global warming, freshwater eutrophication, and ecotoxicity.

The results underscore the critical areas where the fashion industry must focus its sustainability efforts, particularly in the production and processing stages. Recommendations are provided for reducing environmental footprints through improved resource efficiency, adoption of renewable energy sources, and implementation of robust environmental management systems. The thesis also addresses the challenges of greenwashing and emphasizes the importance of transparent and accurate sustainability reporting.

This thesis thus aims to contribute to the ongoing discourse on sustainable development in the fashion industry, providing valuable insights and practical solutions for enhancing environmental performance and achieving long-term sustainability goals.

CONTENTS

1. INTRODUCTION

Environmental issues are among the most significant challenges of the 21st century and they present a critical concern for corporations aiming to combat climate change. In 2015, countries from around the world acknowledged the gravity of this issue by signing the Paris Climate Agreement. This accord commits to limiting the increase in Global Average Temperature to "well below 2°C above pre-industrial levels" while attempting to restrict it to 1.5°C (Salman, Long, Wang, & Zha, 2022). Industrial production and supply chain activities used to be the reason for local, small-scale environmental concerns; however, they have now evolved to having drastic global effects. Industrial activities currently contribute to a variety of environmental issues ranging from water pollution and hazardous waste management to global changes in climate (Sarkis & Zhu, 2017).

When discussing industries and environmental sustainability, it is important that the fashion industry is taken into account. The fashion industry is said to be one of the largest industries in the world and is known for its dynamic nature, holding a considerable proportion of the global revenue. As per the recent “GITNUX Marketdata Report (2024)”, the industry accounts for 2% of the total worldwide GDP, is valued at about US$3 trillion. This vast sector is limited not only to apparel and their retail operations, but also includes critical processes such as the production of required raw materials, sourcing, manufacturing, and logistics.

On the other hand, the fashion industry is said to be one of the most environmentally impactful industries as well. Approximately 9% of the total Greenhouse Gas (GHG) emissions are estimated to be generated from the whole industry, while it also requires high consumption of resources (Ponte, Liscio, & Sospiro, 2023). Furthermore, over the decades, as the fashion industry evolved, a significant development that took place is the exponential growth in “fast fashion”, which can be described as quickly and efficiently adapting products to new trends and tastes (Sull & Turconi, 2008). With the advent of fast fashion, due to its short turnaround time from design to manufacture, and the increased rate at which consumers purchase and discard apparel, fast fashion has revolutionized the fashion industry. This phenomenon has not only altered consumer behaviour and fashion cycles but has also raised significant environmental concerns due to increased resource use and waste generation (Gabrielli, Baghi, & Codeluppi, 2013).

There are several environmental impacts caused by the operations of the global fashion industry; ranging from high energy consumption to the intensive use of toxic chemicals, a large number of examples can be seen to highlight the importance of achieving environmental sustainability in the fashion industry. As per a report published by the European Apparel and Textile Confederation (EURATEX) (2024), only 0.8 percent of the “Textile, Clothing, Leather and Footwear” sector in Europe made use of renewable sources for energy. Earlier, it was also reported that the sector produces the highest amount of post-consumer waste i.e. approx. 6 million tons, out of which only 33 percent is collected for re-use and recycling (2022). Such examples further prove that there is an increasing need for research and development towards environmental sustainability in the fashion industry. Several methodologies have thus also been developed, aiming to monitor whether organizations' performances are in fact sustainable or not. Two such methodologies are Life Cycle Assessment (LCA) and Organizational Life Cycle Assessment (OLCA).

The LCA and OLCA are multi-criteria methodologies, used to evaluate the environmental impacts generated by the production of a specific product, a certain process, or by a complete organization. They assist companies in making strategic and technological decisions, improve their position in the global value chain, and adapt their product lifecycle management to meet the growing demand for environmentally friendly products and services from consumers.

This thesis explores various pieces of scientific literature and discusses multiple sub-topics surrounding environmental sustainability in the fashion industry such as industrial policies and regulations, tools and certifications available for achieving environmental sustainability, and sustainability monitoring techniques.

Furthermore, the case of an apparel manufacturing organization has also been studied. It assesses the overall environmental performance of said organization, adopting a Life Cycle approach, while finally making suggestions on how to improve their performance ratings and achieve a higher degree of sustainability. For this purpose, the OLCA methodology has been adopted and executed using the "SimaPro" LCA tool.

The case study therefore also helps to answer a few important questions. First and foremost, it discusses and analyses possible ways of achieving sustainability in the fashion industry. Secondly, it discusses how OLCA can be an efficient tool to quantify the environmental burdens produced by organizations working in the industry. Moreover, it helps us to identify the benefits of implementing the OLCA methodologies in fashion centred organizations. Finally, the thesis also presents the challenges that organizations may face while assessing their environmental impacts.

2. SUSTAINABILITY & THE FASHION INDUSTRY

2.1 Sustainability

“Meeting the needs of today, without compromising the ability of future generations to meet their own”. The preceding statement accurately summarizes the gist of the term “Sustainability”. While it may be simple to define, there are numerous intricate layers to achieving more sustainable processes and products; meaning that there could be many reasons that lead to a process being unsustainable, varying amounts & intensity of the effects caused by such processes, and various techniques to make said processes more sustainable. On a broader scale, there are said to be 3 dimensions of sustainability; namely Environmental, Social and Economic Sustainability. Environmental sustainability refers to the preservation of natural resources and maintaining the state of the environment in a liveable condition for future generations. Social sustainability encompasses primarily the maintenance of societies’ functions in contexts such as justice and equity, community building, inclusion, diversity and the preservation of culture and heritage. Similarly, Economic Sustainability means that a certain level of economic activity can continue indefinitely which inherently would depend on efficiently using resources, providing adaptable growth opportunities and maintaining a resilient economy (Vinci, D’Ascenzo, Ruggeri, & Zaki, 2024). That being said, to achieve sustainable development, it's important to define the concept in terms of relevant metrics and its main components, as well as adopt an integrated approach (Fabietti, 2013); following which it could become possible to quantify, in terms of sustainability, the performances of various industrial and domestic sectors.

Moving on, this thesis focuses particularly on environmental sustainability and how it is affected by the fashion industry. However, it would not be wrong to state that eventually all three dimensions of sustainability could be considered inter-linked to each other and in order to achieve truly sustainable processes, all dimensions must be taken into account.

2.2 Environmental Sustainability: Italian, European, and Global Contexts

In the recent few years, there has been an increased focus towards environmental sustainability; specifically, on quantifying environmental performances and the means to achieving improved degrees of sustainability. Extensive research has been conducted and developments are being made not only in Italy and Europe, but all around the world. Furthermore, new policies, regulations, and methodologies are gradually being introduced by regulatory bodies to make industrial processes more sustainable.

Since this thesis focuses primarily on industries in Italy, it is imperative that the current state of policies and regulations regarding environmental sustainability in Italy is discussed.

Italy has been engaged in initiatives that promote and disseminate sustainable production models in line with the Paris Agreement and UN Sustainable Development Goals 2030 with a goal of driving the country towards a low-carbon economy (Italian Ministry of Environment and Energy Security, 2023).

An extensive framework is continuously developed consisting of policies and regulations in accordance with the European Union's goals and directives. Italy's National Energy and Climate Plan-NECP (Italian Ministry of the Environment and Energy Security, 2024), for example, introduces pathways to achieve climate and energy goals by 2030. It particularly focuses on reducing GHG emissions, adoption of renewable energy resources, and increased energy efficiency in industries.

The waste management policies in Italy, guided by the Environmental Consolidated Act (Legislative Decree No. 152/2006) also aim to reduce industrial waste to minimal levels and achieving improved resource efficiency (ICLG, 2024).

Similarly, in efforts to reduce GHG emissions, Italy also takes part in the EU Emission trading scheme. This provides producers with the opportunity to receive incentives through the adoption of cleaner technologies (Directorate-General for Economic and Financial Affairs, 2023). The EU Emission Trading System (ETS) could be considered one of the most important and compelling steps taken towards reducing industrial GHG emissions (Ellerman, Convery, & Perthuis, 2010).

Evidently, most policies and regulations in Italy align with those put forward by the European Commission. The European Union (EU) has implemented several strategies, directives and regulations aimed at improving sustainability and ethical practices in various industries, including the fashion sector.

Among recent strategies adopted by the EU, one key element is The European Green Deal 2020. In essence, it aims to achieve climate neutrality in the EU by 2050 (Szpilko & Ejdys, 2022). In order to combat threats such as environmental degradation, the EU green deal attempts to reduce net GHG emissions to zero and achieve economic growth independent of resource use.

Another significant legislative measure is the EU Corporate Sustainability Reporting Directive (CSRD) (European Commission, 2022), brought into effect from January 2023, and can be considered as an important step on the road towards sustainability. This set of amendments aims to align the regulations regarding non-financial and sustainability reporting with the EU Green Deal and the EU Biodiversity Strategy 2030; along with expanding the scope of non-financial reporting requirements to a higher number of firms. It also aims to provide a uniform framework for the reporting of sustainability performances, and to promote ethical corporate conduct.

Furthermore, the EU Corporate Sustainability Due Diligence Directive (CSDDD), requires organizations to conduct in-depth investigations into the environmental and human rights effects. These requirements are not only for organizations within the EU, but also for those that are part of its supply chains (Bueno, Bernaz, Holly, & Martin-Ortega, 2024). As a result, external stakeholders are pushed towards adopting sustainable practices as well, leading to a reduction in harmful environmental impacts on a broader scale.

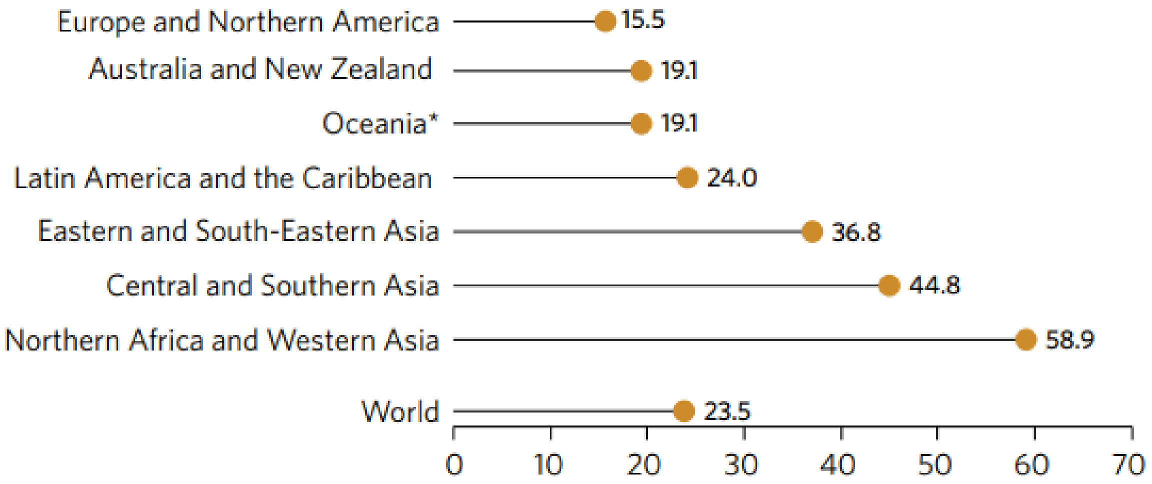
Moreover, The EU microplastics initiative attempts to limit the amount of microplastics released into the environment, such as those derived from synthetic textiles, presenting measures for controlling and reducing microplastic contamination from textile products. It also proposes restrictions on the purposeful use of microplastics in products as well as techniques to catch microfibers during washing, it also encourages research into alternatives to microplastics and technology that limit microfiber release (ECHA, 2023). These restrictions, presented by the European Chemicals Agency (ECHA) were adopted by the European Commission in September 2023.

The EU has also taken a strong stance against the use of Forced Labor. As per a recent press release by the European Parliament, EU member states and European Commission authorities will have the power to investigate goods, supply chains and producers suspected of using forced labour. If it is established that a product was made using forced labour, it will be banned from being sold on the EU market, including on online platforms, and shipments of these products will be stopped at the EU borders (Press Room - European Parliament, 2024).

Globally as well, from carbon pricing to green industrial strategy, economic ideas have had a considerable impact on climate policy. From 1990 to 2017, the World Bank and other influential international institutions OECD shaped policy recommendations on climate. Conventionally, economic growth and environmental conservation were thought to be weakly correlated. However, by the middle of the 2000s, the green growth discourse, emphasizing the strong relation between environmental conservation and economic growth, had been widely accepted (Meckling & Allan, 2020).

An extremely significant development regarding environmental sustainability was the publication of the United Nations' Sustainable Development Goals (UN SDGs). The 2030 Agenda for Sustainable Development, agreed by all UN Member States in 2015, established a shared framework for peace and prosperity for people and the planet both, by 2030, and in the future. Goal 12 of the agenda spoke about sustainable consumption and production and achieving that transition by adopting sustainable manufacturing and limiting waste generation. It also emphasizes that nations should have achieved higher recycling rates by 2030. Furthermore, organizations should adopt environmentally sustainable processes and maintain credibility and transparency while presenting their sustainability performances. Resultantly, sustainability reporting has increased globally, approximately 70% of companies under check were publishing sustainability reports in 2021 (United Nations, 2023). In their report, the UN have graphically represented this increase as well, as shown in Figure 1.

Furthermore, the United Nations Environment Program (UNEP) for example, has played a significant role in the road towards environmental sustainability. Until the end of 2023, there were several on-going and successful initiatives being led by the UNEP. These initiatives include projects such as the sustainable management of the Congo river basin, the UN-REDD program which financed the restoration of forests in 17 countries, and the Intergovernmental Negotiating Committee on Plastic Pollution in order to develop a tool to control microplastic pollution (UNEP, 2023).



[1]

Figure 1: Percentage Increase in number of companies publishing sustainability reports, between 2020 and 2021

The global concern regarding environmental sustainability has also been seen to address the fashion industry repeatedly. At the United Nations Katowice Climate Change Conference in December 2018, The United Nations Framework Convention on Climate Change (UNFCCC), in collaboration with the global fashion industry, commenced the program titled "Fashion Industry Charter for Climate Action". In essence this charter focuses on aligning the practices of the fashion industry with targets set forth by the Paris Agreement 2015. Concisely put, the charter's mission is "to drive the fashion industry to net-zero GHG emissions no later than 2050", presents several goals including, but not limited to, a reduction in emissions, developing pathways for decarbonization, improving the quality and credibility of sustainability reporting, using sustainable materials, and increasing energy efficiency (United Nations Framework Convention on Climate Change, 2021).

2.3 Most Impactful Sectors: The Case of the Fashion Industry

Although textiles and clothing have existed for more than a millennium, the concept of the fashion industry came into existence during the mid-1800s, and since its inception, the fashion industry has continuously been growing and evolving. Initially the industry comprised primarily of custom-made clothing, hand designed as per individuals' tastes and preferences. During the next century as global trade and capitalism grew, and technology advanced, factory-based mass production was established, leading to exponential growth of the fashion industry.

Manufacturing was now being done in massive quantities, and products were being sold through retailers at pre-determined prices. Even though it emerged from Europe and America, the fashion industry soon transformed into a globally connected sector; to the extent that currently the supply chain of one single manufacturing organization could be spread throughout the world. For example, in several cases, raw materials are sourced from one country,

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[1] *Excluding Australia and New Zealand

production takes place in another one, while the products could be sold in several different countries.

Following the automotive and technology industries, the textile industry is the world's third biggest manufacturer. During the latter part of the twentieth century, most of the textile production, especially that of clothes, was relocated to the Asia region in order to benefit from low labour rates and the absence of sustainability regulations. This keeps the industry's actions hidden from most consumers, consequently shifting the burden of the negative impacts of manufacturing to individuals in the global south who manufacture most of our clothing (Monseau, Sorsa, & Salokangas, 2024).

Nowadays, this industry is one of the most important sectors of a country's economy, as it contributes a big share to the GDP of said country by boosting the production, imports, and exports, as well as being a source of employment In 2024, it is expected to grow further by 3-5% (McKinsey & Company, 2023). However, as the industry grows, the negative impacts associated with it grow as well. In recent years, there have been heightened concerns regarding the fashion industry's impact on the natural environment.

Moving forward, this thesis reviews the various threats that the fashion industry poses to the environment, and the diverse set of factors that causes them. The fashion industry, according to global statistics such as those published by the European Environment Agency (EEA) and the United Nations Statistics Division (UNSD) etcetera, can be said to be one of the leading contributors to several of the threats that our environment currently faces. Various academic researchers have also explored the impacts caused by activities of the fashion industry which help us to further understand said impacts and their causes.

Approximately 6% of the total EU consumption impacts come from clothing (Šajn, 2019). Similarly, textile consumption in Europe in 2020 was the fourth leading contributor to climate change from a global life cycle perspective (European Environment Agency, 2022). The fashion industry, having vast and significant environmental impacts, has been receiving criticism over the years; for its lack of attention towards environmental and social concerns (Niinimäki, et al., 2020).Several challenges are faced along the industry's value chains; It is one of the highest resource-consuming industries, consisting of widespread supply chain networks across the world, along with having rapid production and consumption cycles (Hur & Cassidy, 2019).

One of the major concerns that the fashion industry presents is the high consumption of water, consuming approximately 1.5 trillion litres of water per annum (Woensel & Lipp, 2020). The principal reason being that one of the main raw materials for the industry is cotton, which provides about 25% of the world's total textile fibre (Zhang, et al., 2023). Ranging from water scarcity to the depletion of water quality, there are multiple environmental impacts of cotton production (Chapagain, Hoekstra, Savenije, & Gautam, 2006). Additionally. freshwater is used by the production segments of the fashion industry extensively in several wet processes including sizing, bleaching, washing, dyeing, and finishing (Chen, Shen, Liu, Yang, & Wang, 2021); further adding to the Water Footprint of the industry.

Similarly, the extensive use of chemicals and dyes acts as a leading contributor to the water pollution caused by the fashion industry. As explained by Rita Kant (2012), the dyeing segment of the fashion industry uses an enormous amount of chemicals, such as various organic solvents, which can be toxic and poisonous to humans. Another article states that even before the dying process, large amounts of harmful chemicals are also used for the bleaching and washing phases (Gordon & Hill, 2015). Wastewater from such production plants may be full of harmful substances and when dumped untreated into waterbodies, poses a grave threat to the quality of water.

Furthermore, the fashion industry has a highly globalized nature. Meaning that first, the required materials come from several different parts of the world, additionally, not all processes may be carried out in a single location. The textile/fabric may therefore have travelled a significant distance before being available for retail. All this transport, leads to a high amount of carbon emissions, of course depending on the mode of transport that is chosen (Marcketti & Karpova, 2020).

As per another recent paper, the fashion industry makes a significant contribution to climate change, accounting for up to 10% of global carbon emissions. In 2018, the fashion industry alone was responsible for approximately 2.1 billion metric tons of GHG emissions, with fast fashion accounting for half of this total. By 2030, the industry is expected to emit nearly 2.8 billion tons of greenhouse gases annually (Li, Zhou, Zhao, Guan, & Yang, 2024).

Another considerable impact of the industry's globalization is the amount of solid waste generated by different segments of the industry. These linear value chains are comprised of enormous amounts of manufacturers and consumers, while there is almost no recycling or reuse being performed throughout the chains (European Environment Agency, 2019). The rise of fast fashion further adds to the problem of waste. As tastes and trends change rapidly, people tend to buy the latest pieces of apparel while throwing away the old ones, consequently adding to the waste generated by the industry (Remy, Speelman, & Swartz, 2016). The waste can be broadly categorized into two categories: Industry waste, and post-consumer waste. Industrial waste can be defined as the waste produced during the manufacturing process (Wang, 2010), this includes textile scraps, spoilt raw material, and packaging scraps etc. The post-consumer waste includes apparel products that are discarded at the end of their useful lives, along with packaging material which has a very short useful life (Shirvanimoghaddam, Motamed, Ramakrishna, & Naebe, 2020).

2.4 Marketing Sustainability: Environmental Certifications

As it has been previously discussed, several environmental threats have been presenting themselves over the years, however, because of this many developments have also been made to combat such threats. Among the tools that have been developed for achieving environmental sustainability in industries, Environmental Certifications play an important role in promoting sustainable practices and transparency (Baker & McNeill, 2023). A sustainability certification or label is a tool that can be used to communicate, the attributes of a product that are not apparently visible by the product itself and are related to the sustainability of the product (Lee, Bae, & Kim, 2020).

Furthermore, as discussed by Lin and Ma (2023), international brands are now pressing enterprises to achieve green certifications. These certifications have become a vital instrument for assessing vendors and assuring environmental performance along the value chain; severely affecting the textile-related sectors.

Currently, various environmental certifications exist and are being used by diverse industries around the world. This thesis reviews and describes a few of these certificates, and how they can be useful to the fashion industry.

Environmental certifications may help to improve the competitive position of clothing companies as well as enhance sustainability awareness throughout fashion supply chains (Oelze, Gruchmann, & Brandenburg, 2020), the cited authors' assessment mainly analyses the "Bluesign" certification. This certification aims to eliminate all harmful substances that may be used throughout a product's life cycle, along with establishing and monitoring standards of production (Bluesign).

Another common certificate or eco-label, that can be found on millions of products around the world, is the "OEKO-TEX Standard 100" (Muthu, 2015). This standard also analyses the complete product life cycles and processes to check for the presence of any harmful substances in alignment with regulatory acts such as "The Consumer Product Safety Improvement Act (CPSIA)" and "Regulation on the registration, evaluation, authorization and restriction of chemicals (REACH)" (OEKO-TEX).

Similarly, the Global Organic Textile Standard (GOTS) is a comprehensive set of requirements that must be met for a textile to be labelled as organic. Developed by a group of four international organizations from around the world, these requirements pertain to the material used while also exploring the processes to verify that organic material has not been contaminated by contact with inorganic material (International Working Group on GOTS, 2008).

As an extension of the "Cradle to Cradle" philosophy, there exists also the "Cradle to Cradle" certification. Instead of focusing on reducing the negative footprint of organizations, it aims to improve the positive footprint. In order to obtain a "Cradle to Cradle" certification, products/processes are analysed across five different categories, namely material health, material reutilization, renewable energy, water stewardship and social fairness. This certification, rather than having a binary status of certified or uncertified, allots organizations or products with different levels of certification ranging from basic to platinum. The allotted level of certification depends on the mentioned analysis categories (Toxopeus, Koeijer, & Meij, 2015).

Finally, often claimed to be the most widely adopted certification is the ISO 14001. First published by the International Organization for Standardization (ISO) in 1996, reviewed in 2015 (Noia & Nicoletti, 2016), the ISO 14001 provides the required framework for setting up an Environmental Management System (EMS). An EMS may be defined as the official combination of practices and policies aimed at mitigating the harmful environmental effects of a facility or organization (Darnall, 2006). ISO 14001 outlines a systematic strategy to handling environmental challenges inside a company. Its main objectives are to mitigate negative environmental impacts through process control and technical advances and to promote continuous improvement beyond minimum regulatory compliance. It also aims to build structured processes for issue solving and improvement, this includes personnel training, extensive documentation, and regular auditing procedures (Jiang & Bansal, 2003).

2.5 Corporate responsibility: the risk of "Greenwashing"

In current times, with the increased global focus towards environmental sustainability and implementation of new regulations regarding sustainable practices, more and more organizations are compelled to monitor their activities and produce reports regarding their performances. With this however, concepts such as greenwashing emerge, that further contribute to environmental harm (Alizadeh, Liscio, & Sospiro, 2024).

The report titled "The seven sins of greenwashing", published by TerraChoice Environmental Marketing (2009), defines greenwashing as inaccurately presenting the environmental performance of an organization or falsely claiming a product to be environmentally friendly. The authors of this report further define the different acts or "sins" that are categorized as greenwashing. The first sin of greenwashing is to present only certain aspects of a process that are sustainable while withholding other factors that might be harmful to the environment. Secondly, claiming that a product/process is sustainable without providing any proof of stated practices. Moreover, providing vague and irrelevant information, holding no real value in terms of achieving and promoting sustainability, is also considered as greenwashing. Then there is the sin of "Lesser of two evils", whereas a product in a certain category may be labelled as sustainable or eco-friendly, however the category itself is unsustainable. Another common form of greenwashing is simply lying, i.e. making completely false claims. For example, a firm may label their product as being certified to "Bluesign", without having obtained the certification. Similarly, false labels exist as well. This means that a product may be labelled with a certification that does not exist or hold no significant value; the authors refer to this as "fibbing".

The term "greenwashing" was first introduced in 1986 by an environmentalist named Jay Westerveld; since then, several researchers have explored the phenomenon in order to understand its negative effects and ways to eliminate it.

If greenwashing is not curbed in time, the consequences over time can be severe, as a smaller number of stakeholders and investors are willing to participate in the production of green products for the market, as a result, encouraging businesses to engage in destructive activities (YANG, NGUYEN, NGUYEN, NGUYEN, & CAO, 2020). For current stakeholders, greenwashing may have a positive impact through additional profits. However, it would have a negative impact on the society as a whole. Additionally, it would have a negative impact on potential investors and stakeholders, wishing to participate in the production of truly sustainable processes. Due to the reduced trust between organizations and stakeholders, as a result of greenwashing practices, potential stakeholders would now be hesitant to invest in green (Solomon & Rhianon Pel Edgley, 2008) (Guo, Tao, Li, & Wang, 2015).

In the California Management Review Journal, Delmas and Burbano (2011) describe the different types of firms in regard to greenwashing. They are listed as vocal green firms, silent brown firms, silent green firms, and greenwashing firms. The greenwashing firms are considered to be the worst as along with having poor environmental performance, they make claims of being environmentally friendly and thus avoiding corrective action. Any of the firms can transition to any of the four categories depending on whether or not they alter their practices: by either improving/deteriorating their environmental performance, or by changing their sustainability reporting practices. The authors also discussed potential causes that lead to greenwashing, which have been summarized in Figure 2[2].

Resultantly, regulatory bodies around the world have started taking initiatives to tackle the threat of greenwashing as well. In the United States for example, the Federal Trade Commission (FTC) first published the “Green Guides” in 1992, providing guidelines regarding green marketing. They were most recently updated in 2012 to ascertain that environmental declarations are honest and not misleading (Federal Trade Commission-US Government). Similarly, in February 2024, the EU parliament released a directive regarding “empowering consumers for the green transition”, specifically focusing on regulations relevant to environmental marketing (Grothaus, et al., 2024). The (EU) Directive 2024/825 aims to prepare consumers for the green transition by introducing specific rules in Union consumer law to tackle unfair commercial practices. It focuses on providing clear, relevant, and reliable information to consumers to enable informed purchasing decisions and promote sustainable consumption patterns (European Parliament; Euorpean Council, 2024). Similarly, in its Directive 2022/2464/EU, namely the Corporate Sustainability Reporting Directive the EU aims to tackle the greenwashing phenomenon by amending the regulations regarding non-financial reporting.

The Competition and Markets Authority (CMA) in the United Kingdom has taken a relatively strict stance regarding greenwashing, particularly within the fashion industry. The CMA earlier begun an investigation on three fashion brands and their claims about environmental sustainability. On March 27th, 2024, it was communicated that the three brands have now signed undertakings on compliance with environmental reporting guidelines by the CMA. Additionally, an open warning was issued to actors in the fashion industry, urging them to honestly comply with the “CMA Guidance on Environmental Claims on Goods and Services”, or to be prepared for unforeseen investigations, followed by corrective action (Competition and Markets Authority - Government of the United Kingdom, 2024).

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[2] (Delmas & Burbano, 2011)

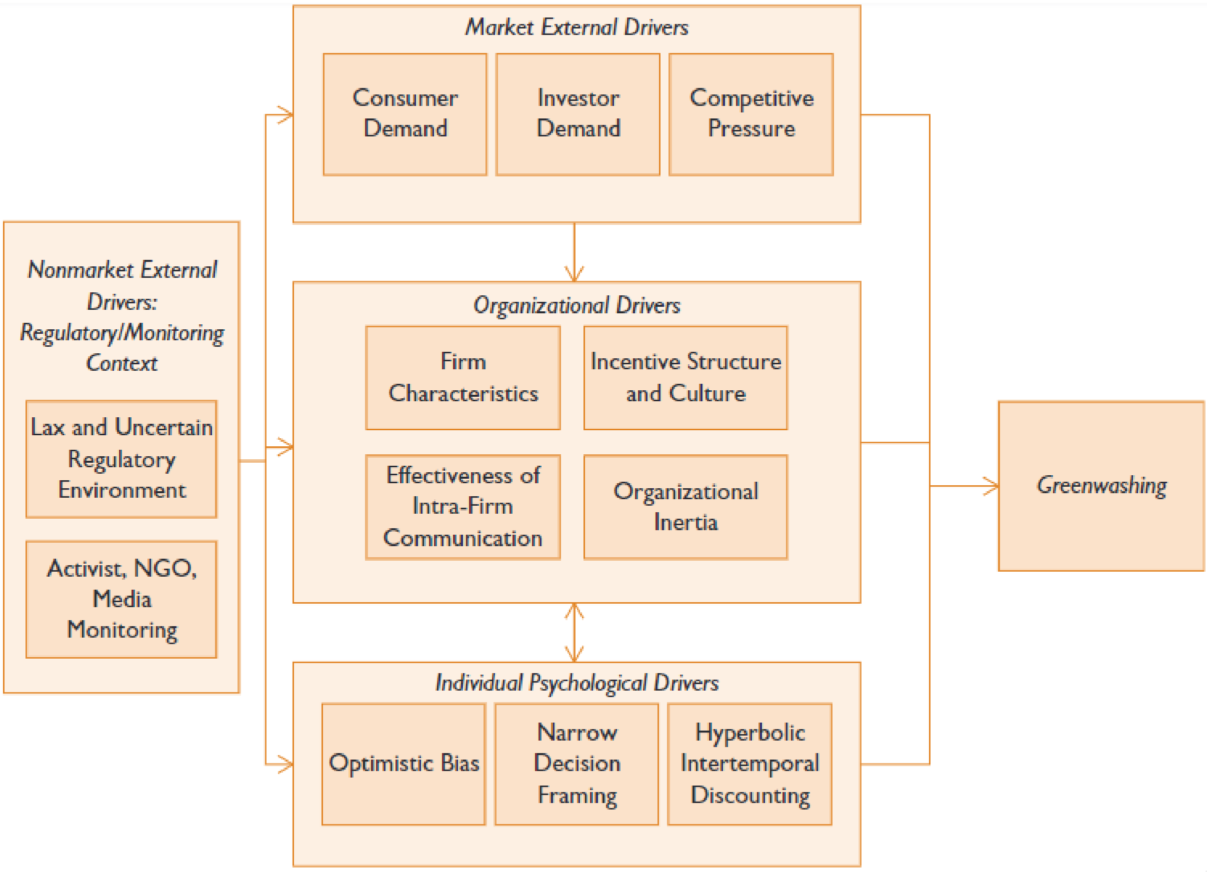

Figure 2: Drivers of Greenwashing

3. ASSESSING SUSTAINABILITY

3.1 Performance Monitoring: Importance and Tools

So far, the definition of sustainability has been discussed, and the global policy stance regarding sustainability. The dynamic policies and regulations attempting to promote environmental sustainability indicate that the world is now on a path towards achieving sustainable processes. This thesis also explored the different ways in which the fashion industry contributes to environmental impacts such as high consumption of water, the release of toxic chemicals, and the release of GHGs etcetera. However, to assess whether an organization/product is actually environmentally sustainable, it is extremely important to define environmental sustainability in terms of numbers and data. Attempts to measure sustainability began in the 1980s, the next logical step was to translate the notion into a realistic and quantifiable reality. As the notion of sustainable development became more widely accepted, there was a need to create indicators and methodologies for quantifying and analysing sustainability levels (Ramachandran, 2000).

Similarly, in his paper published in (1996), Daniel Tyteca argues that we need numerical indicators that help us rate the environmental performance of facilities organizations, and to determine whether the various policies and regulations are indeed effective or not.

For defining the corporate environmental policy, administration of environmental programs, setting of sustainability goals and the verification of fulfilment of said goals, performance monitoring is an extremely important pre-requisite (Verschoor & Reijnders, 2001).

Environmental sustainability measurements assess the impact of an organization's activities on greenhouse gas emissions, climate, and overall environmental health. For example, for the fashion industry, it may include: i) assessing the environmental impact of its supply chain in terms of materiality, including waste generated, water consumption, energy consumption and emissions from indirect and direct activities, ii) transferring raw materials and products from production to consumers and potentially disposing or recycling them. Monitoring, improving the circular economy and sustainability, iii) assessing the well-being of individuals and communities affected by company activities, focusing on factors such as employee safety, health, and socio-economic impact on local communities (Brightest, Inc, 2024). Figure 3[3] shows a few of the impact categories through which indicators can be designed for assessing sustainability.

Baumann and Cowell (1999), suggest that there are several methods and tools that have been designed to monitor and assess environmental performance. These include, but are not limited to, Life Cycle Assessment (LCA), Material Flow Analysis (MFA), Carbon Footprint, and Environmental Impact Assessment (EIA) (Finkbeiner, 2009). Additionally, the tools available for environmental monitoring can be divided into 2 categories, namely, procedural tools and

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[3] Source: https://www.brightest.io/sustainability-measurement

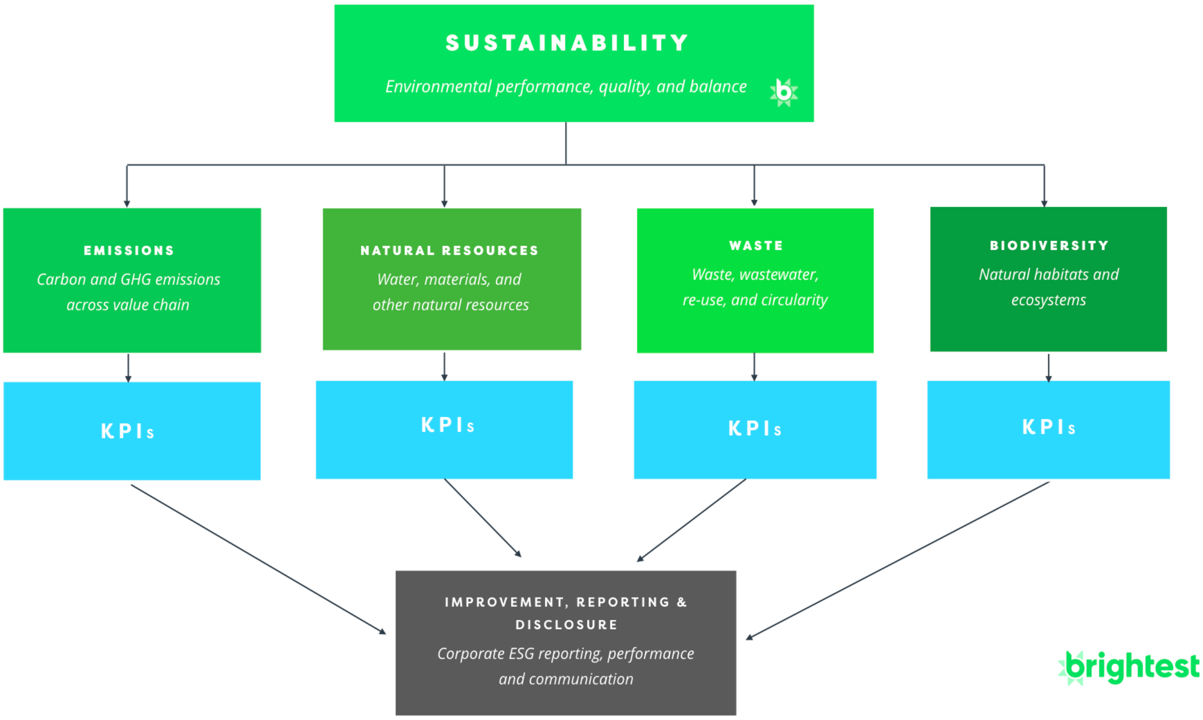

Figure 3: Impact Categories for Indicator Selection

analytical tools While analytical tools concentrate on the technical components of the analysis such as the amount of a certain toxic gas being released, procedural tools emphasize the procedures and their relationships to the sociocultural and environmental decision context, for example the Environmental Management System which provides a framework to develop an EMS. It must be mentioned here that the use of an analytical tool could be included within the structure of one of the procedural tools (Wrisberg, Haes, Triebswetter, Eder, & Clift, 2002) (Finnveden & Moberg, 2005). Moving forward, this thesis explores a few of the commonly adopted tools for environmental performance monitoring.

One of the oldest tools available for assessing the environmental performance of a product or organization is the EIA. It is a procedural tool, first introduced in 1969 by The National Environmental Policy Act (NEPA) (Andersson, Brynolf, Landquist, & Svensson, 2016). As discussed by Christopher Wood (2009), NEPA guides an EIA to be a step by step, iterative procedure. It begins with analysing the proposed alternatives to a certain existing process, the selected alternative is then designed to represent its functioning. At this stage, “screening” must be performed to decide whether an EIA is needed in the selected case. After that, the scope of the EIA must be defined, meaning that the assessment areas included in the EIA should be outlined. Once the screening and scoping processes are done, an EIA report is developed. The report must include, but not be limited to, a description of the chosen alternative and an analysis of the environmental impacts, and severity of these impacts, produced by it. Once the report has been completed, it must be reviewed to verify its credibility. Based on the EIA report, and any analyses related it, it can now be decided whether the proposed alternative is implemented or not. In the case that the proposal is rejected, the aforementioned steps may be reiterated; whereas if the proposal is accepted and brought into practice, the anticipated impacts must be monitored to verify the EIA procedure. These steps may also be illustrated in the form of a flow chart, as shown in Figure 4[4].

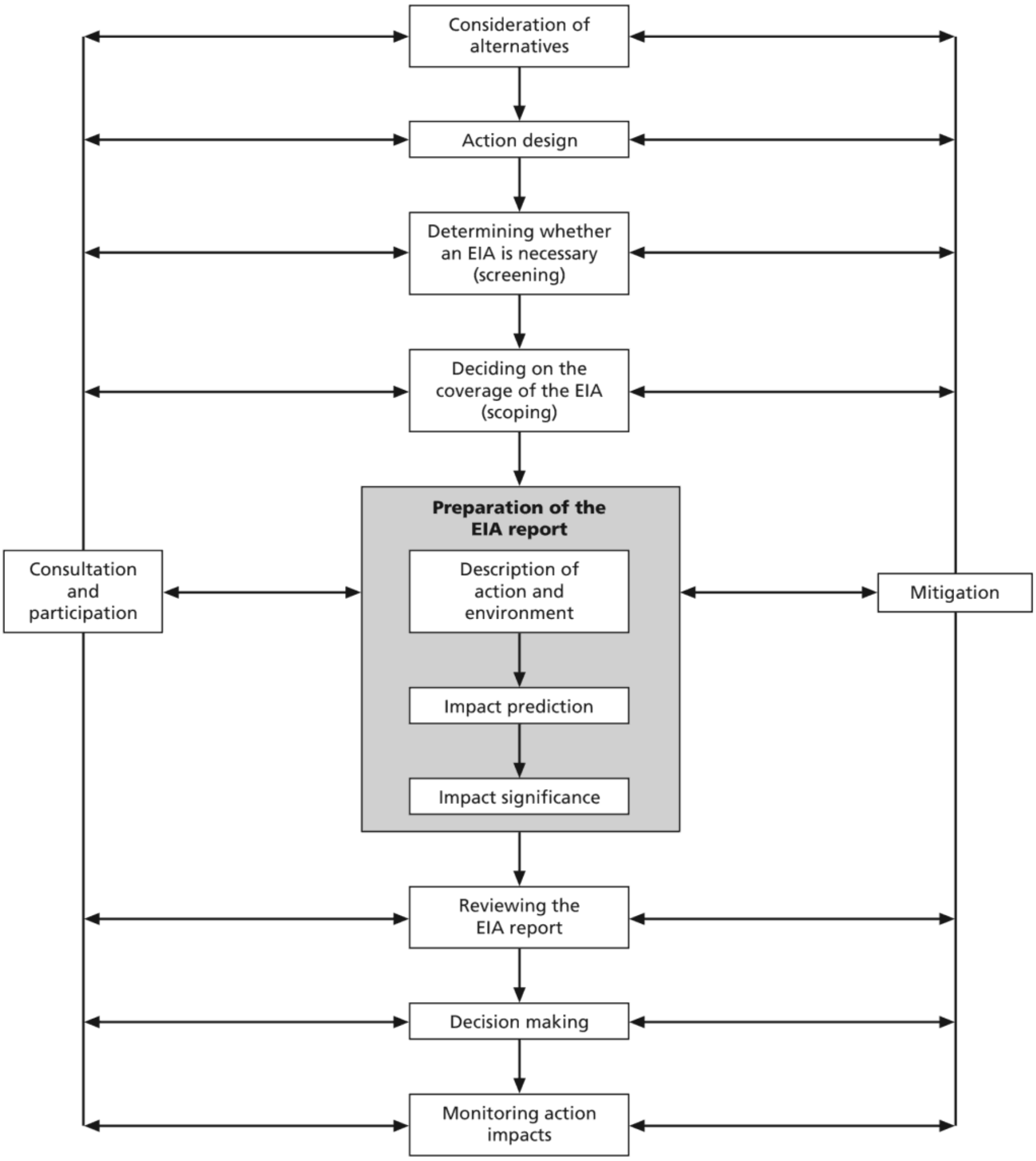

Figure 4: Procedure for EIA

One of the tools in which there has been a growing interest in the last 3 decades is the LCA tool. It is an analytical tool, widely used as an evaluation method that determines and offers information on the environmental effects of goods and services during their entire life cycle (Hellweg & Canals, 2014). Based on results of an LCA study, decision makers and technical personnel can take necessary measures at an early stage of a product, service, or organizations development to prevent harmful environmental impacts, and avoid investing in those projects that will subsequently prove to have a higher environmental impact (Giesen, Cucurachi, Guinée, Kramer, & Tukker, 2020). It would make sense to take into account the comprehensive approach that an LCA offers when attempting to analyse multiple environmental or energy

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[4] Source: (Wood, 2009)

consumption characteristics of a product, and when there is a need to analyse decision making trade-offs related to areas that are environmental hotspots (ICCA LCA Task Force, 2020). In the following sections, Life Cycle Thinking (LCT), LCA and OLCA are discussed thoroughly in terms of their application and the various procedures involved.

Another important methodology that is widely adopted is Material Flow Analysis (MFA). MFA is a fundamental technique in industrial ecology. The flows of resources into and out of a certain societal sector, or part of a sector, can be represented and quantified by MFA in a similar way to how an accountant analyses incoming and outgoing monetary transactions. Furthermore, dynamic MFAs, that address a particular area or system over time, allow for the identification of the materials that are in use and of the "hibernating" stockpiles within a sector (Graedel, 2019). MFA measures in numbers the life cycle of a resource to assess its sustainability. The analysis considers not only inputs and outputs in lifecycle phases, but also interactions with the environment and imports/exports (Fuse, 2012). There exist multiple software that can help conducting a MFA, such as INOSIM Professional (Sulzbacher, Balling, & Schembecker, 2013), STAN (Padeyanda, Jang, Ko, & Yi, 2016), GABI and UMBERTO (Brunner & Rechberger, 2003).

3.2 Life Cycle Thinking

The fashion industry, particularly the fast-fashion model, stands at the second position in terms of pollution, right after oil and gas, while also being one of the highest consumers of energy and natural resources; thus, creating the need for in-depth assessments from a life cycle perspective (Ponte, Liscio, & Sospiro, 2023).

The LCA and OLCA methods are critical to assessing environmental impacts, both of which are rooted in the principles of life cycle thinking. While both methods have the same framework, the main difference between them lies in the subject of analysis.

LCA focuses on the evaluation of a specific product, while OLCA extends its analysis to the entire organization or to a specific part of it, taking into account all associated activities (ISO, 2006) (Martínez-Blanco, et al., 2015). However, it is important to note that the OLCA is not designed for benchmarking between different organizations or for public communication in contexts such as the classification of companies. Instead, its primary use is identifying and facilitating improvements within the organization itself (ISO, 2014). Additionally, LCA is a useful tool that companies can use to avoid greenwashing and make credible claims about their sustainability efforts (Alizadeh, Liscio, & Sospiro, 2024), while OLCA provides insights to organizations in their decision-making based on sustainability principles.

Substantial amounts of academic literature support the study and adoption of Life cycle thinking (LCT), considering it a fundamental concept and method to support sustainable transition. When environmental damage and resource shortages became major challenges in the 1960s, the concept of life cycle assessment was established. Following a stagnant period in the 1970s, the scientific community saw a rise in methodological development, international collaboration, and coordination throughout the 1980s. LCA has now evolved to include a wider range of goods and systems. The development of LCA methodology is ongoing, with a focus on achieving global scientific agreement and standardizing LCA and related approaches (Bjørn, Bey, Georg, Røpke, & Hauschild, 2017).

Several researchers have delved into the topic of LCT and applied the LCA methodology as a means to achieving environmental sustainability, particularly regarding the fashion industry. Roos, et al., (2016), for example, study the environmental sustainability of the apparel sector in Sweden, making use of an LCA-based approach. By presenting environmental issues in textile use, the study explores the environmental performances of the sector, proposing interventions for improvement.

As discussed by Koroneos, et al., (2013), LCT is a crucial approach to assess the environmental sustainability of manufacturing and use. They further explain that Life Cycle Thinking (LCT) considers the environmental, social, and economic impacts of a product throughout its lifecycle, from production to end-of-life. Its highlights include Enhanced Producer Responsibility (EPR), where producers take responsibility for their products from "cradle to grave", and Integrated Product Policy (IPP), which aims to reduce resource consumption and emissions while improving socio-economic performance.

In their paper titled "Life cycle assessment of a leather shoe supply chain", Rossi, et al., (2021), have explored the environmental impacts related to the production of leather shoes. The authors apply the LCA methodology to assess the different stages of the supply chain and determine the environmental hotspots and impacts related to each stage. Furthermore, based on their assessment, they also suggest possible changes that could be made in logistics, raw materials and sourcing of raw materials. The paper further concluded that the adoption of suggested alternatives could result in a 30% reduction of environmental impacts.

Launched in 2002, by UNEP and The Society of Environmental Toxicology and Chemistry (SETAC), The Life Cycle Initiative has played a crucial role in development of LCT concepts. It is a joint effort that promotes LCA and LCT as tools for sustainable development. The objectives of this initiative are to promote knowledge sharing, study the relationship between LCAs and other environmental instruments, improve education, improve the quality of LCA data and procedures, and make recommendations for effective implementation of LCAs. It is divided into three main programs: the Life Cycle Inventory (LCI) program, which creates a peer-reviewed database. Life Cycle Impact Assessment (LCIA) program, which improves impact assessment methodologies. and the Life Cycle Management (LCM) program, which focuses on practical applications in decision-making. By engaging stakeholders and providing educational tools, the program promotes collaboration and sustainable practices in various industries around the world (Haes, Jolliet, Norris, & Saur, 2002).

Furthermore, over the years, there has been an increased mention of LCT in regulations and environmental policies as well. The United Nations (2015) presented the "2030 Agenda for Sustainable Development", in which the assessment of waste and harmful chemicals across their entire life cycles has also been addressed. This resulted in further developments to be made in the LCT domain, while encouraging industries to adopt the approach in order to achieve their sustainability goals. As can be seen from policies such as the "1992 Ecolabel Regulation" or the "2019 Green Deal", life cycle issues in the EU are of particular interest (Sala, Amadei, Beylot, & Ardente, 2021).

The Organization for Economic Co-operation and Development (OECD) issued the "Due Diligence Guidance for Responsible Supply Chains in the Garment and Footwear Sector" in 2017. This guide intends to assist firms in implementing the "due diligence" guidelines outlined in the OECD Guidelines for Multinational firms along the textile and footwear supply chains. It aims to minimize negative repercussions from organizations' operations and supply networks. The rules also aim to encourage responsible company activity, aligning with government goals.

The EU, in its Waste Framework Directive (European Commission, 2008) specifically mentions the management of waste, adopting a life cycle approach. More recently, amendments were proposed to the directive in which a particular focus towards textile waste can be seen. It again emphasizes the importance of life cycle approaches in order to tackle the resource intensive nature of the textile industry. It also presents guidelines regarding the end-of-life management of textiles and how the responsibility should be placed with the producers (European Commission, 2023).

3.3.1 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a scientific method for assessing and measuring the environmental impacts of a product, service, or process throughout its entire life cycle. The ISO 14040 and 14044 standards (ISO, 2006) covers all life cycle stages including raw material extraction & processing, production, distribution, use, and disposal, i.e. a cradle-to-grave approach. The function of an LCA is to represent the environmental burden that a product/process inflicts, in a quantitative manner. By the grouping of different kinds of input/output flows different products/processes may be compared. LCA also emphasises environmental hotspots which require improvement.

The concept emerged in the late 1960s because of growing concern about the scarcity of various natural resources, particularly oil. In fact, the Midwest Research Institute (MRI) conducted the first study to quantify the inputs (resources) and outputs (Emissions and waste) required for The Coca-Cola Company's beverage packaging materials in 1969 (Moutik, Summerscales, Graham-Jones, & Pemberton, 2023). Since then, LCA has become an important complementary tool in decision-making and implementation. It can be applied to identify product/process stages where the environmental performance could be enhanced, and resultantly to assist in strategic decisions, define priorities for focus, and the design of products and processes.

As per the ISO standards 14040:2006 (E), the framework of the LCA is comprised of four broad stages, as can be seen in Figure 5. First the practitioner must define the goal and scope of the study, followed by the definition of the complete inventory, i.e. The Life Cycle Inventory Analysis. Once all the inputs and outputs have been accounted for, the Life Cycle Impact Assessment (LCIA) is performed; and finally, an interpretation of the LCIA results must be presented.

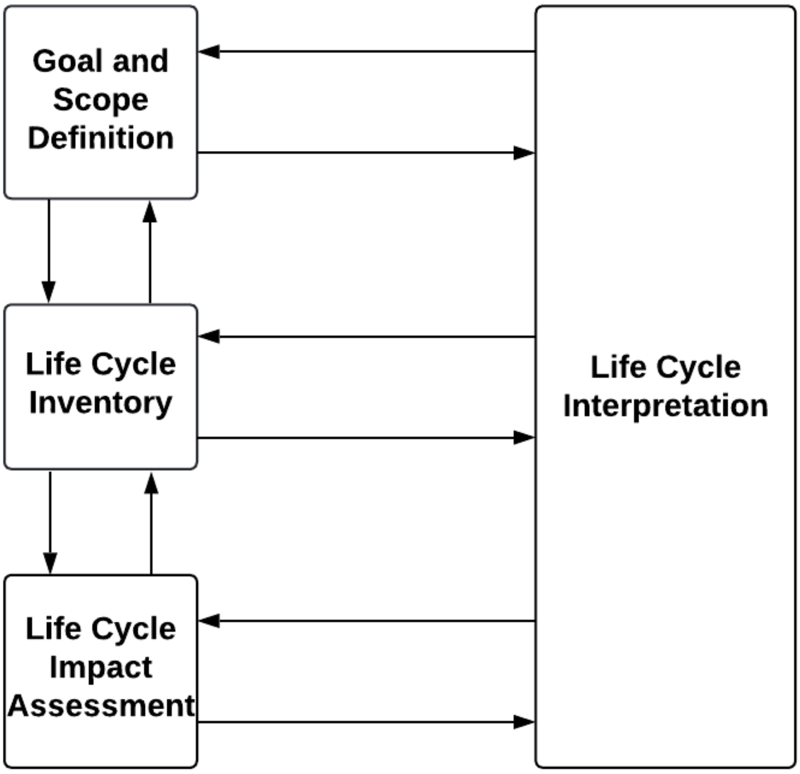

Figure 5: Stages of an LCA

The official standards and guidelines, along with academic literature, further define these stages as such:

Goal and Scope Definition

This is the first step in the start phase of a LCA study, which also helps to determine how the following steps will be performed (Martínez-Blanco, Finkbeiner, & Inaba, Guidance on Organizational Life Cycle Assessment, 2015). It consists of the definition of the object of study, the definition of the functions and functional units of the system, the limits of the system, as well as the cut-off rules, assumptions, and limits. In order to effectively achieve the stated objectives, it is necessary to adequately clarify the scope of the study to ensure its compatibility and relevance in terms of its breadth, depth, and detail.

When defining the purpose and scope, the desired applications of LCA results should be clearly defined. The aim should be clear and comprehensive, and emphasis should be on what the objective of the assessment is to achieve. For example, it may be a matter of comparing the environmental impact of self-generated solar energy use with the use of electricity from the market for a particular product/process. At this stage, the functional unit should also be defined, which is an important factor that provides the basis for comparison. It defines the unit of measurement for analysis and determines the activity or object (e.g. product, service, or process) under consideration while defining the duration and functionality of the unit under consideration. For example, the environmental effects of making 1 T-shirt that remains in use for a certain period. Defining the goal and scope also includes defining the limitations of the system: it means which parts of the lifecycle and what processes will be involved in the analysis. To represent these ranges, a schematic diagram can be used, which shows what the assessment includes and what is excluded from it. The boundaries should define the approach chosen i.e. Cradle to Cradle, Cradle to Grave, Cradle to Gate, and Gate to Gate, a general outline of these approaches can be visualized in Figure 6. System limitations should define not only physical limitations, but also impact assessment methods that will be applied, the indicators that will be used to assess the performance, and the quality of the data used to include discrepancies and assumptions made in the data.

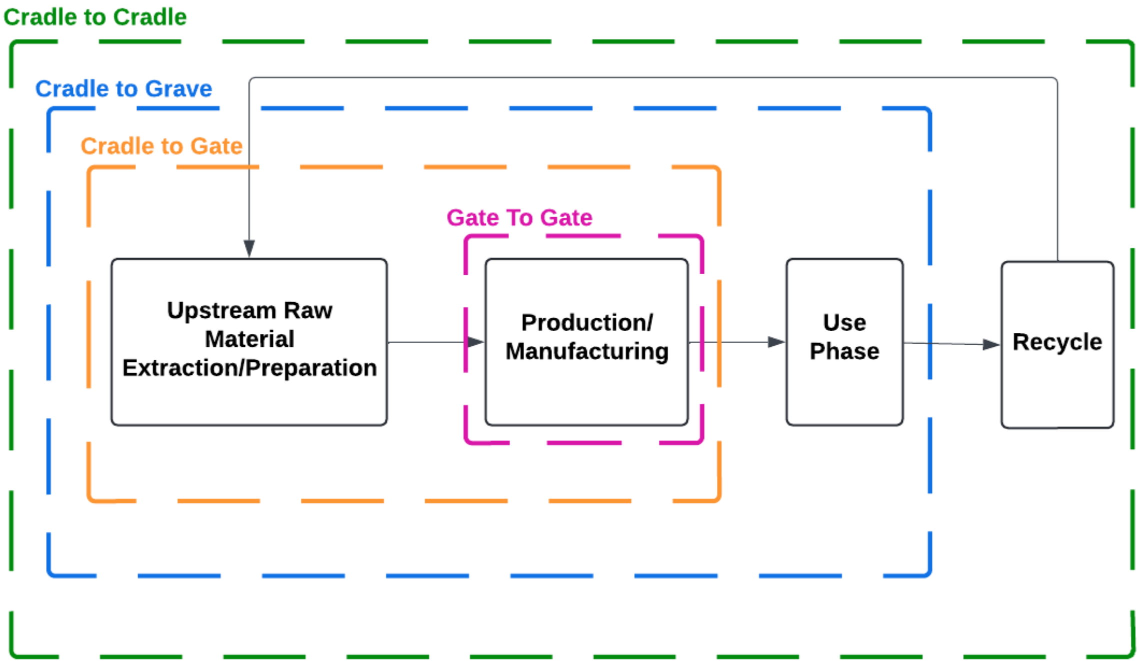

Figure 6: Approaches for defining the system boundaries

<u>Life Cycle Inventory</u>

The second stage, known as Life Cycle Inventory (LCI) analysis, is defined by the ISO as "the phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle " (ISO, 2006). It consists of collecting data for the measurement of related flows, including various inputs of materials, energy, and transportation, as well as outputs such as emissions to air, water and soil, and solid waste during the product's lifetime. The collected data must be in alignment with the established boundaries, meaning that only the materials and processes included in the system boundary should be accounted for in the inventory.

It is important to remember that the data collected must be accurate and genuine to ensure the quality of the LCA. This data can be obtained from primary and secondary sources. Primary data is obtained directly from the specific processes studied, for example through direct interviews with the organization. This type of data is the most reliable and accurate, but difficult to obtain because it's usually undisclosed to the public. Secondary data is usually taken from existing literature and various LCA databases, such as "Ecoinvent", "GABI", “Product Environmental Footprint”, and the "European Life Cycle Database (ELCD)". These secondary sources may not show the same level of accuracy as the primary data, therefore the results obtained may be inaccurate. Figure 7[5] represents some most used databases for inventory analysis.

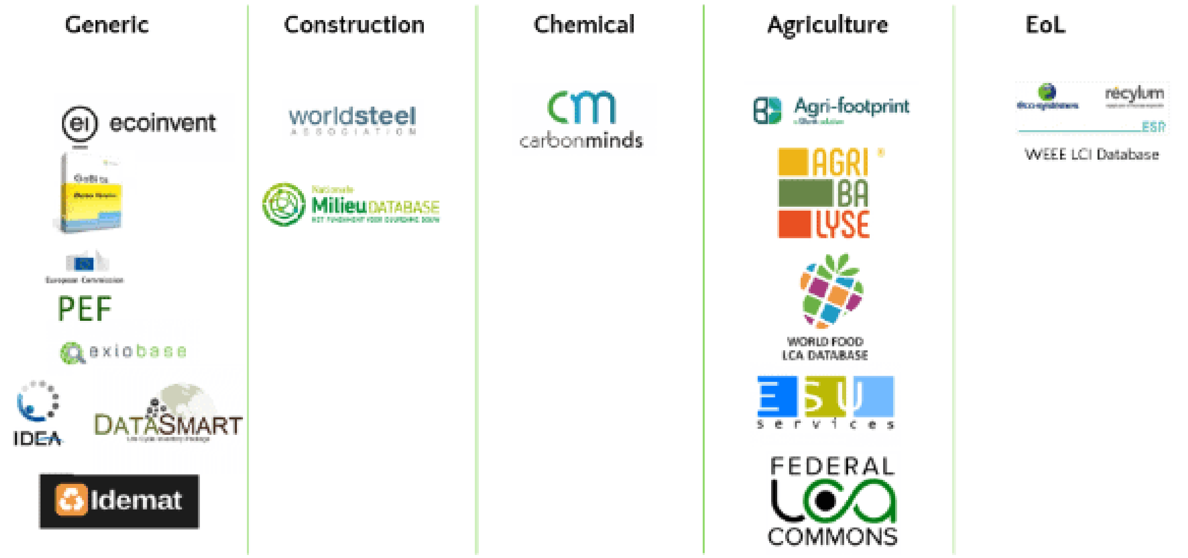

Figure 7: Commonly used databases for Life Cycle Inventory Analysis categorized by sectors

Life Cycle Impact Assessment (LCIA)

The third phase of an LCA study comprises of selecting the impact assessment categories, against which the performance of the product under study will be assessed. The evaluation is done based on the data collected during the LCI phase, in order to understand the environmental impacts of each material and process included in the system boundary.

To begin the LCIA, the assessment method must first be selected. Various methods are present and can be chosen depending on the goal and scope of the LCA, such as the “ReCiPe 2016”, “Environmental Footprint Method v3.0”, “ILCD midpoint and endpoint” and “Ecological Scarcity 2006” methodologies. These methodologies differ with each other primarily based on the indicators included and whether they are “Midpoint indicators” or “Endpoint indicators”. From the initial introduction of an emission to the final impact, there is a chain of causes and effects. At the end of these chains lie endpoint indicators, which include the 3 principal damage categories, i.e. Impact on human health, impact on environment, and resource availability. Indicators that lie in the middle of the chain, and contribute to the principal impact, are the midpoint indicators (Meijer, 2021). For example, the increased concentration of a certain GHG in the air would be considered a midpoint indicator, which would eventually lead to the endpoint indicator i.e. impact on environmental health. Among the midpoint impact indicators,

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[5] Source: https://ecochain.com/blog/lci-databases-in-lca/

there are several impact categories that can be assessed based on the method selected for impact assessment. These include, but are not limited to, Global Warming Potential, Human Toxicity, Eutrophication, Resource Depletion and Water Ecotoxicity. Some examples of assessment methods and the midpoint indicators they include can be seen in Table 1[6].

Table 1: Examples of Impact assessment methods and included impact categories and

METH-ODS	Acidification	Climate change	Resource depletion	Ecotoxicity	Energy Use	Eutrophication	Human toxicity	Ionising Radiation	Land use	Odour	Ozone layer depletion	Particulate matter/ Respiratory inorganics	Photochemical oxidation
CML (baseline)	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	No	Yes	No	Yes
ReCiPe Midpoint (H)	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
Eco-Scarcity 2006	No	No	Yes	No	No	No	No	No	No	No	No	No	No

Figure 8[7] represents the updated framework for the LCIA phase, as presented by the UNEP/CETAC Life Cycle Initiative in which midpoint indicators can be seen as impact categories while endpoint indicators are shown as damage categories. It should be noted that the list of impact categories is not complete and could include several others depending on the methodology. Then the classification is performed, in which all elements in the inventory are now linked to the relevant endpoint impact categories like human health, environmental health, and resource exhaustion. This is further followed by the characterization process. During the characterization stage of LCIA, each inventory item and resource flow is quantitatively modeled based on the applicable environmental mechanism. It employs a characterization model to compute specific material specific characterization factors, which reflect the possible

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[6] Adapted in part from (Acero, Rodríguez, & Ciroth, 2015)
[7] Source: (UNEP/SETAC Life Cycle Initiative, 2016)

impact of each elementary flow in a single unit for the category indicator.

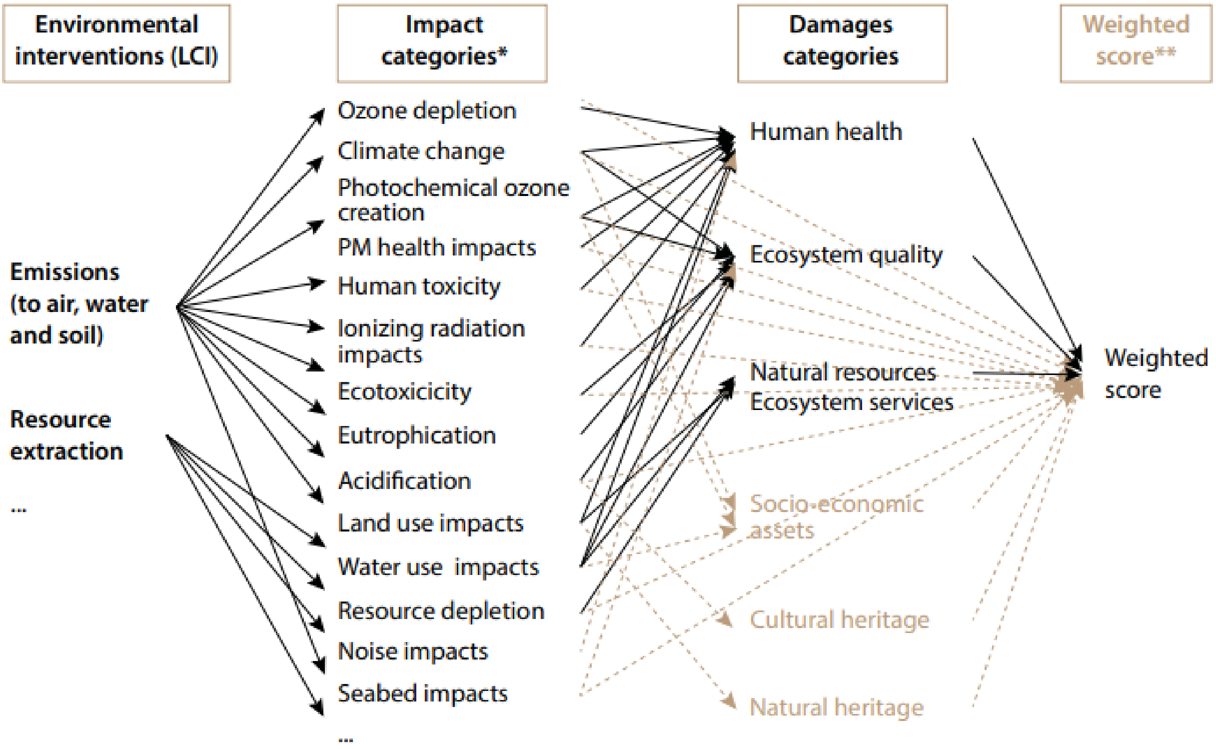

Figure 8: Updated Framework for LCIA

Multiplying characterization variables with inventory data yields category indicator findings in standardized units, such as kilograms of CO_2 equivalents for greenhouse gasses relevant to climate change. For different impact assessment methods, various characterization factors are present in existing literature, lifecycle databases and tools for assessment. The following equation can be used to calculate a certain impact indicator:

$$Impact\ Value = \sum_{x} CF_x \times Amount_x$$

Where CF_x: Characterization Factor for emission "x"

According to the ISO 14044:2006, the previously discussed steps are essential to the LCIA phase (Hauschild, et al., 2013). However, once the impact results for all category indicators have been calculated, results can further be refined to achieve useful reference information for the analysis. ISO, in its guideline defines the Normalization and Weighting steps as optional. Normalization is the calculation of the value of the category indicator results in comparison to some reference data. The purpose is to better understand the relative size of each indicator issued in the product system under consideration. It is the process of dividing the results of an indicator by the default reference value. The reference system should be selected based on the coherence of the geographical and time dimensions of the ecosystem and the value of the reference system. Weighting consists of assigning quantitative weights to all classes of impacts to express their relative importance. Results from different impact categories must be converted using numerical factors based on value options.

Interpretation of Results

The final phase of an LCA entails interpreting results obtained from the inventory and impact assessment phases, thus concluding the LCA to provide useful information for decision-making. Of course, as a conclusion to the entire assessment, the result interpretation will reflect the overall quality of the assessment being conducted. Therefore, this stage should first consider the completeness of the analysis, how sensitive the data is to changes, and the consistence of the analysis results. Following which areas of high significance must be identified with regards to inventory data, along with impact categories most relevant to the study being performed and the process areas' contribution to said impact categories. Furthermore, as per the ISO 14040 and 14044 series, the interpretation phase may also include suggestions and recommendations about potential improvements that could be adopted in areas with high impacts.

3.3.2 Organizational Life Cycle Assessment (OLCA)

Based on the guidelines for LCA presented in the ISO 14040 and 14044 standards, the European Commission (2013) presented its Environmental Footprint (EF) methodology for products and organizations. The commission recommended a detailed set of recommendations for measuring and presenting the EF of products and organizations while considering their entire lifecycles, and therefore making use of the LCA methodology. The framework for assessing an organization's EF was outlined by the EC as can be seen in Figure 9[8].

In 2014, The ISO officially published the specific technical requirements for conducting an LCA for organizations, or Organizational LCA (OLCA). Titled ISO/TS/14072, this technical specification defines OLCA as the collection and subsequent analysis of all the throughputs and potential environmental impacts being produced by an organization and not just a single product. Also being built upon the ISO 14040 and 14044 standards, it further describes OLCA being similar to an LCA in multiple aspects, while also explaining in detail the steps particular to conducting an OLCA. It also emphasized the broad applicability of the specifications to include all sizes of organizations as well as particular segments of an organization. Thus, the ISO/TS/14072 has largely standardized the application of LCA for organizations.

Another extremely significant development was the publication of the "Guidance on Organizational Life Cycle Assessment" in 2015. The UNEP/CETAC Life Cycle Initiative had launched its flagship project in early 2013, titled "LCA of Organizations", with most part of the project dedicated to development of the guidance. The guidance has been designed in compliance with the ISO 14040 and 14044 standards, European Organizational Environmental

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[8] Source: Adapted from (European Comission, 2013)

Footprint (EOF) standards, and the GHG Protocol standards, while also taking into consideration feedback from various stakeholders. The project and guidance aim to elaborate the different criteria and steps of an OLCA and consequently ease the application of an OLCA, along with elaborating the different applications of OLCA and increase the usefulness of OLCA for organizations and SMEs.

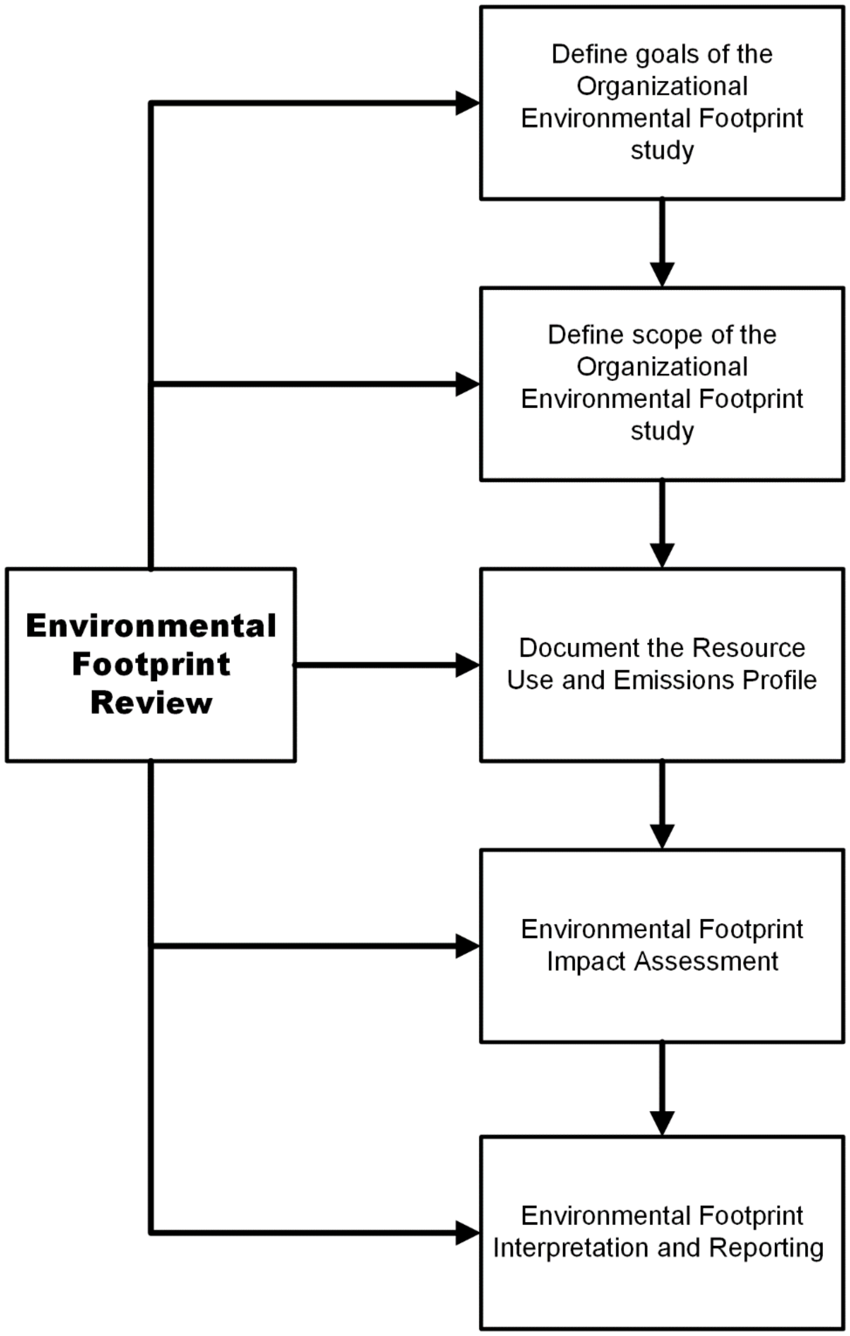

Figure 9: Phases of an Organisational Environmental Footprint study

The Life Cycle Initiative further went on to test the implementation and usefulness of their guidance in the "Road-testing" phase of the LCA of Organizations project. The road-testing included almost ten different industries from varying sectors and regions in order to highlight the applicability of the Guidance on OLCA in different scenarios while also identifying challenges that may be faced while implementing the guidance; the organizations included in the road-testing are listed in Table 2[9].

Table 2 : Organizations for Road-testing of Guidance on OLCA

Case Study	**Region Headquarters**	**Sector**
Accor S.A.	France	Hotels and resorts
BASF	Germany	Chemicals
Colruyt Group	Belgium	Retail
Inghams Enterprises Pty Limited	Oceania	Poultry
KPMG	Netherlands	Professional services
Mondelēz International, Inc.	USA	Food processing
Natura Cosméticos S.A.	Brazil	Consumer goods - Cosmetics
Shiseido Company, Limited	Japan	Consumer goods - Cosmetics
Storengy (GDF SUEZ)	France	Natural gas
Unilever	UK	Consumer goods
Volkswagen Group	Germany	Automotive

Since OLCA is a relatively new methodology, there is not much existing work relating to it. The Guidance on OLCA, along with its road-testing reports, therefore, plays a significant role in the promotion and application of the OLCA methodology as presented by the ISO TS/14072. The lack of academic literature also makes it complicated for practitioners to adopt the methodology, for example the none of the organizations in the road-testing study focus on the fashion industry; thus, this thesis aims to contribute towards the practice and development of OLCA.

As is the case with the ISO TS/14072, the Guidance on OLCA does not explain in much detail the elements of an OLCA that are common to an LCA as well. However, it does explain any updated requirements and elements that are specific to an OLCA. The overall framework remains the same, consisting of the same four steps as an LCA. The complete and unambiguous definition of the goal and scope is required for both LCA, and OLCA. Both methodologies can be re-iterated to obtain improved quality of results, require defining a unit of reference and a

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[9] Source: (Guidance on Organizational Life Cycle Assessment, 2015)

system boundary. Of course, both methodologies adapt a life cycle approach, thus also requiring large amounts of high-quality data. The procedures for allocation of recycling and reuse data are the same for both methodologies. Additionally, both, LCA and OLCA, methodologies make use of identical methods for impact assessment, presenting a comprehensive set of impact assessment indicators. A critical review of the assessment is also required before disclosing to the public (Martínez-Blanco, Finkbeiner, & Inaba, 2015). The differences in both methodologies as outlined by the guidance can be seen in Table 3[10].

Table 3: Comparisons in LCA and OLCA

	Product LCA	**Organizational LCA**
Goal and Scope Definition		
General	A sole product LCA, in itself, does not provide all the information to make decisions on an organizational level, as O-LCA does.	The granularity of O-LCA does not give information on how to improve the environmental performance of an individual product.
	Unit of analysis and consistent boundaries are mostly required for comparative assertions. Product LCA can also be used for performance tracking if it is embedded in the right technical and organizational manner.	Apart from transparency reasons (due to the large complexity of the system), the need of a unit of analysis and consistent boundaries is for environmental performance tracking of the organization.
Unit of analysis	Functional unit and the reference flow are defined according to the main function/s of the product.	. The reporting organization defines the organization per se (i.e., the unit of analysis) and the reporting flow ideally represents the quantification of its product portfolio (amounts, unit, revenue, etc.).
	Functional unit specifies which the function of the product used for comparison is.	In the reporting organization, it is specified which part(s) of the organization are included, determining whether the whole organization is considered and using the consolidation methods.

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[10] Source: (Guidance on Organizational Life Cycle Assessment, 2015)

	The reference flow refers to a certain number of units of the product assessed – as many as needed to fulfil the functional unit.	The reporting flow very often includes more than one product – as many as the organization is offering in its portfolio.
Time issues	Generally, results of the study are largely time-independent during a reasonable period.	The results reported by an organization may be different from one year to the following one, due to changes in the amounts or types of products in the portfolio, among others
	Very often, the environmental impacts are calculated according to the life span of the product.	The environmental results of the organization are referred to a given reference period that should be defined in the reporting organization.
System boundary	The units/steps of the life cycle are processes, materials, energy, intermediate products, etc.	The units are those organizations in the value chain of the organization.
	The system boundary is derived from the type of product.	The definition of the reporting organization is the determining issue for stating system boundary.
	No distinction is done between direct and indirect impacts.	The direct and indirect activities and associated impacts are differentiated within the system boundary
Life Cycle Inventory Analysis		
General	The involvement of stakeholders is encouraged (beyond the study commissioners) in the peer review of the study.	It is recommended, as far as possible, the involvement of the suppliers, especially for providing specific data of their operations and own suppliers.
	The outcomes may be of course updated but it is not common to do so periodically.	An ulterior improvement of data collection efforts and data quality is particularly recommended. Due to the performance tracking objective, O-LCA is expected to be applied to the organization in consecutive years.
Supporting activities	Those activities that are not directly linked to the production are usually not considered.	O-LCA does consider activities generally disregarded in product LCA (e.g., business travel, leased

		assets, heating, cleaning services, managerial offices).
Data collection	The use of specific data for the product assessed is expected.	The use of more generic or extrapolated data is expected, particularly in big organizations providing complex products.
Multifunctional situations	System expansion is one option to avoid allocation.	In general, system expansion is not used, due to the risk of inconsistent or poorly representative substitution scenarios.
Life Cycle Impact Assessment		
General	Basically, the same methods are used for product and organizational LCA once the inventory has been compiled. In O-LCA, the use of inventory-level indicators, apart from impact categories, is common.	
Life Cycle Interpretation and Uncertainty		
General	Comparison between products is possible and can be communicated, given the comparability of the assessment approach.	External communication of comparative assertions is discouraged, but performance monitoring and reporting is sought.
Reporting and Communication		
General	Communication of results (e.g., through EPDs) is mainly targeted to consumers.	Organizational reporting (e.g., sustainability reporting) mainly aims to communicate the results to, consumers, institutions and society

Currently, conducting a manual LCA or OLCA is difficult and impractical due to the extensive data processing, computation, and analyses required for such an assessment. The use of software thus becomes necessary, particularly when dealing with a high number of substances and compounds. Therefore, in order to help organizations, practitioners and researchers conduct LCA studies, several software and tools have been developed such as OpenLCA, SimaPro, GaBi, Umberto, and Ecochain. As an OLCA is very similar to an LCA, some software designed to perform an LCA can be used to perform an OLCA as well. One of the most widely used and applauded software is SimaPro. It offers multiple vast in-depth databases along with several different methods for impact assessment. It also allows for the results to be represented graphically in the form on bar charts and Sankey diagrams, thus helping to better portray the relative impact situation and identify environmental hotspots, two such examples can be seen in Figure 10 and Figure 11.

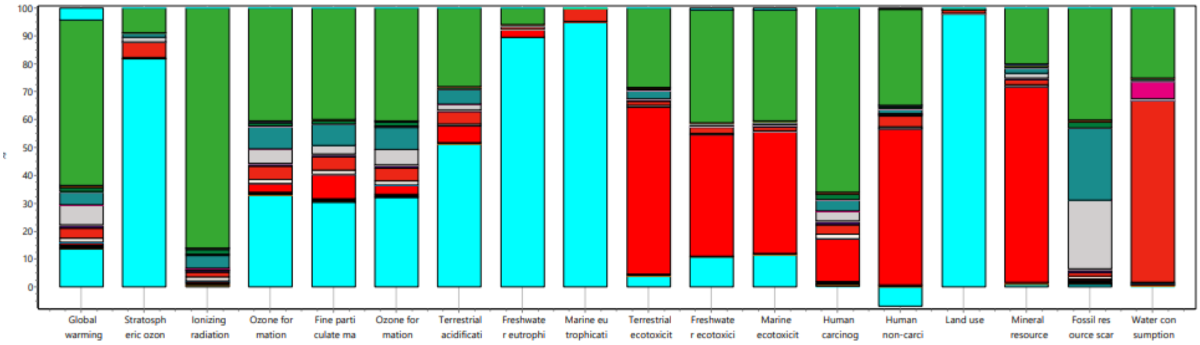


Figure 10: Characterization Results generated on SimaPro

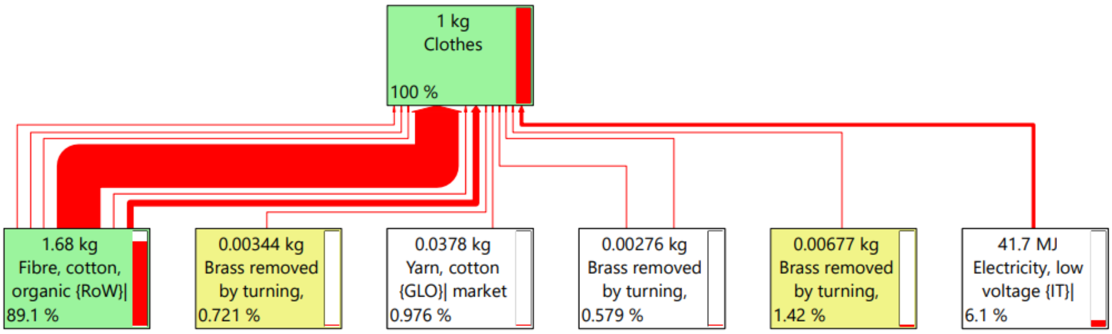


Figure 11: Example of a Sankey Diagram for the component wise contributions generated on SimaPro

4. CASE STUDY

4.1 Goal and Scope

The objective of this analysis is to evaluate and monitor the overall environmental performance of the company under study, employing the Organizational Life Cycle Assessment (OLCA) methodology (ISO/TS 14072), within the framework of the Life Cycle Assessment, in accordance with the ISO 14040 and ISO 14044. This comprehensive assessment aims to quantify the environmental impacts associated with the company's direct and indirect activities over the reference period of the fiscal year 2023. Focusing on the last year, the goal is to provide a clear and detailed understanding of the company's environmental footprint during this period, facilitating comparison with future annual reports, and so that improvements may be done in areas with high impacts. It should be noted that the results that will be presented through this report may not be used for direct comparative assertions with other companies disclosed to the public, as stated in the ISO/TS 14072.

4.1.1 Reporting Organization

The organization headquartered in Italy, specializes in the design and production of high-quality apparel and fashion. Operating within the apparel and fashion industry, it offers expertise in research, development, prototyping, pattern making, and manufacturing, especially for top brands in the fashion industry. The organization manages the entire process from pattern making to final garment production, ensuring superior craftsmanship and quality. It has a diverse product portfolio in the apparel industry, with products such as shirts, dresses, pants, belts and more. The numbers for all product types, and their total weights have been shown in Table 4.

Table 4: Summary of finished products produced by the organization

Item	Quantity (Pieces/Pairs)	Weight (kg)
Men’s Pants	14636	8049.8
Women’s Pants	7736	3403.84
Children’s Pants	16551	3310.2
Adult Skirts	4332	1299.6
Adult Jackets	3410	2046
Adult Shirts	1713	513.9
Adult Dresses	2619	1309.5
Children’s Jackets	2080	416
Children’s Shirts	35	3.5
Children’s Dresses	58	17.4
Bags	2900	1450
Belts	943	188.6
Boots	5450	5450
Total	**62463**	**27458.34**

The organization’s production process begins with a research and proposal phase, where customer preferences are studied to generate ideas for new products. Raw material samples are procured during this phase. If the ideas and suggestions align with customer needs, the company proceeds to produce the first prototypes. These prototypes are then reviewed for approval. If the prototypes are not approved, the process returns to generating new ideas or modifications. Upon approval, samples are produced for sales campaigns.

After the sales campaign, production orders are received, determining the required quantities for production. Subsequently, raw materials are procured based on these orders. Upon arrival of the raw materials, shrinkage tests are conducted to assess how the fabrics will change dimensions when exposed to water.

The production process formally begins with modelling and development in various sizes. If additional raw materials are required during this phase, they are procured accordingly. Following the modelling phase, the laying and cutting of fabric layers occur, which are performed in-house. After cutting, the fabrics are sewn according to the required dimensions and designs.

Post-sewing, the garments are prepared for packaging. If the packaging is to be conducted in-house, it is done immediately; otherwise, the garments are sent to an external packaging facility. Once packaging is complete, the garments are subjected to a quality check where they are counted and inspected.

If the batch is small enough to be handled in-house, the ironing and finishing processes are completed within the company. Otherwise, the garments are sent to external facilities for ironing and finishing. The washing and treatment of garments are also performed externally. After these processes are completed, the garments return to the company for final packaging.

Packaging involves the use of materials such as polyethylene bags, cardboard boxes, and neutral plastic bags. The transport of garments to and from various facilities, as well as within the production facility, is managed as part of internal logistics. Finally, the distribution of the finished products is managed by the customers themselves.

4.1.2 Reporting Flow

As per the UNEP/SETAC guidelines on OLCA, the reporting flow is a measure of the outputs of the reporting organization. It is a quantitative amount and constitutes the reference for the inventory of OLCA.

This OLCA relies on total quantity of product sales for the year, measured in kilograms. This metric is essential for understanding the scale of the company's output and its corresponding environmental impacts. All the impacts, even outside the production process, are referred to in the reporting flow. The current assessment is performed over a reporting period of 1 year. As presented in Figure 12 on the next page, activities are divided into direct and indirect activities, while indirect activities are further categorized into downstream and upstream activities.

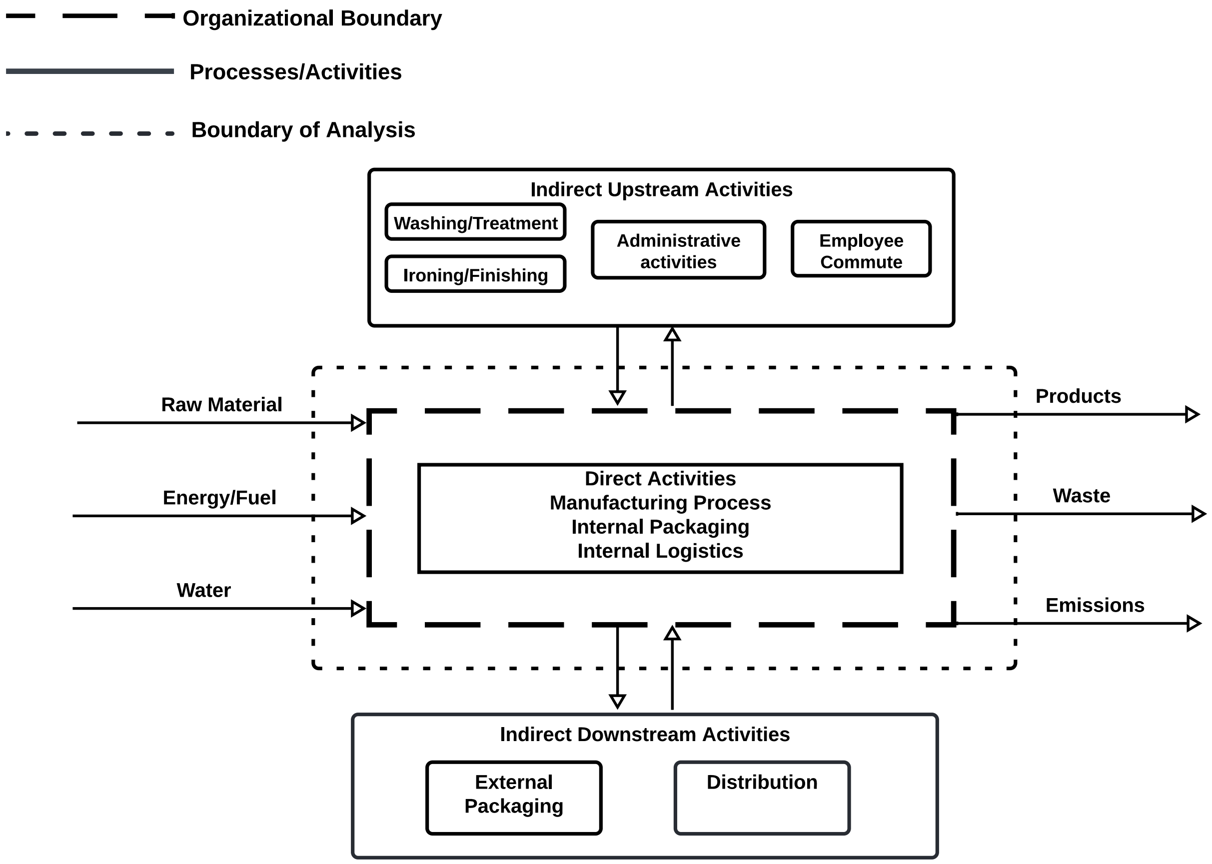


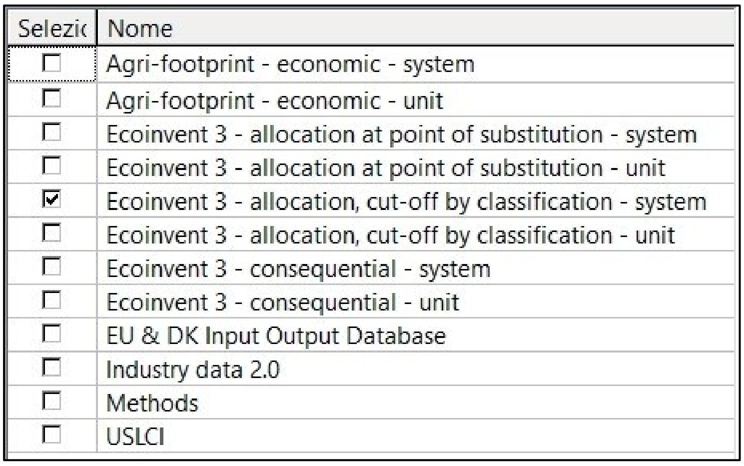
Figure 12: Illustration of material flow and activities within the organization, detailing direct and indirect processes

4.2 Life Cycle Inventory (LCI)

4.2.1 Library

For this study, the software “SimaPro Version 9.1.1” was utilized. Additionally, out of the multiple available libraries, the “Ecoinvent 3” library, specifically the "allocation, cut-off by classification – system" version as shown in Figure 13, was chosen as the primary library. Ecoinvent 3 is a renowned life cycle inventory database, providing comprehensive and consistent data necessary for accurate environmental impact assessment. The chosen version of the library ensures a precise allocation of environmental impacts based on system cut-off criteria, enhancing the reliability of our results.

To gather the necessary data, a series of questionnaires were designed and shared with the organization. These questionnaires allowed for the collection of complete information on each input and output, including details about their weights and materials.



Selezic	Nome
☐	Agri-footprint - economic - system
☐	Agri-footprint - economic - unit
☐	Ecoinvent 3 - allocation at point of substitution - system
☐	Ecoinvent 3 - allocation at point of substitution - unit
☑	Ecoinvent 3 - allocation, cut-off by classification - system
☐	Ecoinvent 3 - allocation, cut-off by classification - unit
☐	Ecoinvent 3 - consequential - system
☐	Ecoinvent 3 - consequential - unit
☐	EU & DK Input Output Database
☐	Industry data 2.0
☐	Methods
☐	USLCI

Figure 13: Illustration of the selected library

4.2.2 Inventory

Organizational Life Cycle Assessment (OLCA), "inventory" refers to the detailed collection and quantification of all inputs and outputs involved in the organization's processes and activities as shown ahead in Table 5.

The inputs for the organization encompass a variety of essential materials and resources. These include raw materials like fabric and linings needed for production, along with packaging materials for internal packaging. Energy carriers such as electricity and gas are vital, as well as fuel for logistics and water for various processes. On the output side, the focus is on the finished products produced and waste generated.

Table 5: Illustration of inputs and outputs of the system

Outputs to Technosphere: Products and Co-products		
Item	**Amount**	**Unit**
Clothes	27458.34	kg
Outputs to Technosphere: Waste and Emissions to Treatment		
Item	**Amount**	**Unit**
Waste yarn and waste textile {RoW}| treatment of waste yarn and waste textile | Cut-off, S	12080	kg
Inputs from Technosphere: Materials/Fuels		
Item	**Amount**	**Unit**
Fibre, cotton, organic (GLO)| market for fibre, cotton, organic | Cut-off, S	35214.68	kg

Fibre, polyester (GLO)| market for fibre, polyester | Cut-off, S	979.76	kg
Brass (GLO)| market for | Cut-off, S	267.116	kg
Carton board box production, with offset printing (GLO)| market for | Cut-off, S	1691.76	kg
Yarn, cotton (GLO)| market for yarn, cotton | Cut-off, S	388.65	kg
Textile, non-woven polyester (GLO)| market for textile, non-woven polyester | Cut-off, S	388.65	kg
Printed paper (GLO)| market for | Cut-off, S	20.052	kg
Polyester resin, unsaturated (RER)| market for polyester resin, unsaturated | Cut-off, S	8472	kg
Textile, woven cotton (GLO)| market for textile, woven cotton | Cut-off, S	50.211	kg
Polyethylene low linear density granulate (PE-LLD), production mix, at plant RER	606.4	kg
Polystyrene, general purpose (GLO)| market for | Cut-off, S	354.5	kg
Natural gas, high pressure (IT)| market for | Cut-off, S	18198	kg
Water, deionised (Europe without Switzerland) | market for water, deionised | Cut-off, S	372000	m^3
Diesel (Europe without Switzerland) | market for | Cut-off, S	16527	kg
Trichloroethylene (RER)| trichloroethylene production | Cut-off, S	120	kg
Polyethylene, low density granulates (RER)| production | Cut-off, S	1578	kg
Packaging film, low density polyethylene (GLO)| market for | Cut-off, S	841	kg
Corrugated board box (RoW)| production | Cut-off, S	2014	kg
Kraft paper, unbleached (GLO)| market for | Cut-off, S	36.9	kg
Inputs from Technosphere: Electricity/Heat		
Item	**Amount**	**Unit**
Electricity, low voltage (IT) | market for | cut-off, S	238206	kWh

4.2.3 Data Refinement

During the data collection process for the Organizational Life Cycle Assessment (OLCA), efforts were made to be as thorough as possible. However, due to some minor gaps in the information provided by the reporting organization, a few assumptions backed by market research were necessary to complete the inventory analysis. These assumptions were crucial to ensure the analysis's accuracy and completeness despite the missing data and were based on findings from a literature review.

Firstly, it was assumed that the fibres and tissues consisted solely of polyester and cotton (as per the relevant compositions), as other materials were present in negligible and varying amounts such as “Elastane” only had a mass composition of 0.07% out of the total cotton fibre used, thus it was considered to be cotton. This assumption is supported by literature indicating that polyester and cotton are the predominant materials used in such applications. For components such as buckles, eyelet rivets, and buttons, brass was assumed to be the primary material. This decision was based on research findings that brass is commonly used for these items, and the organization did not specify the metal types used. Additionally, for labels described by the organization as "calf skin," polyester was used as a proxy material due to the absence of "calf skin" in the available databases. This choice is backed by literature that often uses polyester as a stand-in for unavailable specific materials. This assumption could have had a significant effect on the impact results as the production of calf skin leather poses several environmental threats. In this analysis however, the amount was very small i.e. ~0.13%, therefore it was possible to assume a different material. In cases where there is a significant amount involved, it would be advisable to collect primary data from suppliers of the material. For plastic hangers, polyester resin was assumed as the specific type of plastic was not provided, again aligning with common practices found in literature.

4.3 Life Cycle Impact Assessment (LCIA)

4.3.1 Method

The results have been calculated using the “Ecoinvent 3 - allocation, cut-off by classification - system” library while the method selected was “ReCiPe 2016 Midpoint H”. The Characterization technique is used in the process of transforming inventory data into potential environmental impacts, making it a vital step for evaluating and mitigating the ecological footprint of organization. Additionally, through normalization, the most impactful categories of the whole organization have been identified.

4.3.2 Overall Impact Assessment by Characterization

The impact assessment illustrated in Table 6 provides an overview of the environmental impacts associated with the production of 1 kilogram of clothing across all the impact categories included in the selected impact assessment methodology. Furthermore, the characterization results illustrated in Figure 14 provide a comprehensive analysis of the impacts, in terms of the contribution of each inventory item.

Table 6: Impact Assessment by Characterization

Impact category	Unit	Total
Global warming	kg CO_2 eq	8.46
Stratospheric ozone depletion	kg CFC_{11} eq	$5.06x10^{-05}$
Ionizing radiation	kBq Co-60 eq	0.57
Ozone formation, Human health	kg NO_X eq	0.02
Fine particulate matter formation	kg $PM_{2.5}$ eq	0.01
Ozone formation, Terrestrial ecosystems	kg NO_X eq	0.02
Terrestrial acidification	kg SO_2 eq	0.05
Freshwater eutrophication	kg P eq	0.02
Marine eutrophication	kg N eq	0.03
Terrestrial ecotoxicity	kg 1.4-DCB	33.74
Freshwater ecotoxicity	kg 1.4-DCB	0.67
Marine ecotoxicity	kg 1.4-DCB	0.87
Human carcinogenic toxicity	kg 1.4-DCB	0.22
Human non-carcinogenic toxicity	kg 1.4-DCB	9.32
Land use	m^2a crop eq	18.09
Mineral resource scarcity	kg Cu eq	0.02
Fossil resource scarcity	kg oil eq	3.52
Water consumption	m^3	0.20

The characterization factors quantify the relative contributions of different materials and processes to impact categories such as global warming, stratospheric ozone depletion, ionizing radiation, ozone formation, particulate matter formation, terrestrial acidification, freshwater eutrophication, freshwater and marine ecotoxicity, human carcinogenic and non-carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity, and water consumption.

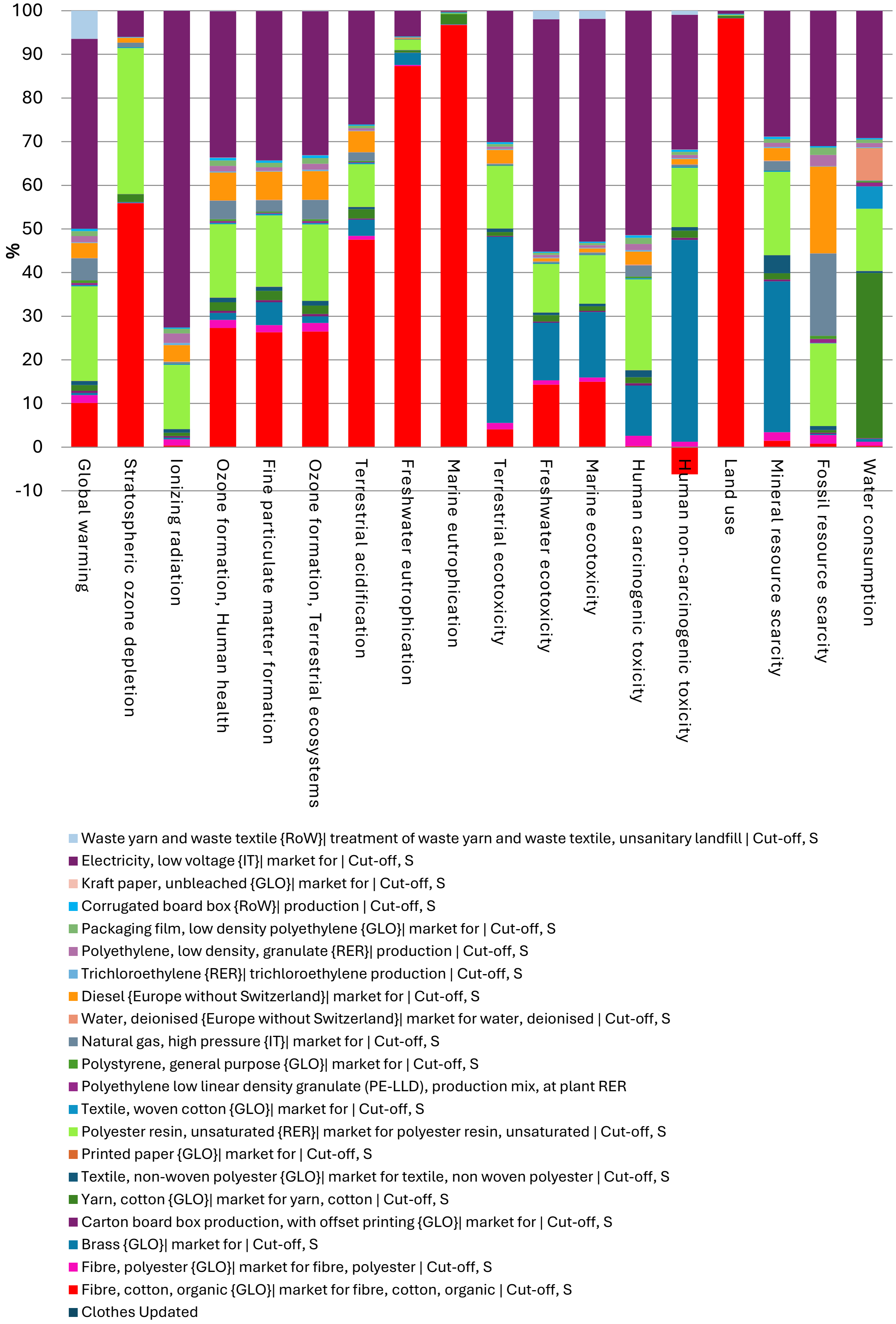


Figure 14: Illustration of Impact Assessment by Characterization Realized in MS Excel

Global warming potential is predominantly driven by contributions from polyester resin and electricity, which together account for a substantial portion of the total impact. The high carbon footprint associated with these inputs is due to the energy-intensive nature of synthetic fibre production and fossil fuel-based electricity generation. Cotton fibre also contributes significantly to global warming, primarily due to the emissions associated with its cultivation and processing.

Stratospheric ozone depletion is mainly influenced by polyester resin, with additional contributions from electricity and cotton yarn. The chemical processes involved in producing polyester and the energy required for manufacturing result in the release of ozone-depleting substances. Similarly, ionizing radiation impact is largely attributed to electricity, particularly in regions where nuclear power is a significant part of the energy mix, with polyester resin and brass also contributing due to their production processes.

In terms of ozone formation (impacting both human health and ecosystems), the primary contributors are electricity and polyester resin. Emissions from these sources play a significant role in ground-level ozone formation, a known pollutant. Cotton fibre also contributes, likely due to the use of nitrogen-based fertilizers in agriculture. Particulate matter formation, which is associated with respiratory health risks, is primarily driven by electricity production, with additional contributions from polyester resin and cotton yarn.

Terrestrial acidification is significantly influenced by emissions from electricity and polyester resin production, driven by sulphur and nitrogen oxide emissions. Cotton fibre also plays a role in acidification, reflecting the impact of agricultural inputs. Freshwater eutrophication is primarily caused by cotton fibre, highlighting the nutrient runoff from cotton agriculture, particularly the use of fertilizers. Polyester resin also contributes to a lesser extent.

When it comes to freshwater and marine ecotoxicity, polyester resin and brass are the leading contributors. The toxicity associated with synthetic fibre production and metal processing pose risks to aquatic ecosystems. Electricity and cotton fibre also contribute, reflecting the broader environmental impacts of energy production and agriculture.

Human carcinogenic and non-carcinogenic toxicity impacts are notably driven by brass, due to the release of heavy metals during production. Polyester resin and electricity also contribute significantly, driven by the emission of harmful chemicals and pollutants. Land use impacts are largely dominated by cotton fibre, given the extensive land requirements for cotton cultivation. Polyester resin contributes as well, due to the land required for petrochemical extraction and processing.

In terms of mineral resource scarcity, brass is the major contributor, reflecting the extraction and depletion of metals used in its production. Polyester resin and electricity also contribute to this category, driven by the mining of minerals required for their production. Fossil resource scarcity is primarily driven by polyester resin, as it is derived from petrochemicals, with electricity also contributing significantly, particularly when generated from fossil fuels.

Finally, water consumption is overwhelmingly dominated by cotton fibre, reflecting the high usage of water in cotton agriculture. Polyester resin also contributes, though to a lesser extent, due to the water-intensive processes involved in its production.

Overall, the impact assessment underscores the significant environmental impacts associated with the production of polyester resin and electricity, which emerge as major contributors across multiple impact categories. Cotton fibre also shows substantial impacts, particularly in categories related to water consumption, eutrophication, and land use. These findings highlight the urgent need for sustainable practices and the adoption of cleaner technologies in the textile industry to mitigate these environmental impacts.

Moving on, for a more in-depth analysis, by leveraging the normalization technique the most impactful categories have been obtained as compared to the characterization ones.

4.3.3 Impact Assessment by Normalization

The Normalization results for producing 1 kg of clothes illustrated in Figure 15 show that freshwater eutrophication is heavily influenced by organic cotton fibre, which causes significant nutrient runoff. Marine eutrophication has relatively minor impacts from polyester, brass, and electricity. Both freshwater and marine ecotoxicity are notably affected by polyester, brass, and organic cotton, due to the release of harmful substances into water bodies from manufacturing and agricultural practices. For human carcinogenic and non-carcinogenic toxicity, the primary contributors are polyester, brass, and electricity, likely due to emissions and pollutants during their production. Overall, the chart emphasizes that ecotoxicity impacts are most pronounced in the lifecycle of clothes, driven primarily by organic cotton, polyester, and brass, with electricity also playing a significant role.

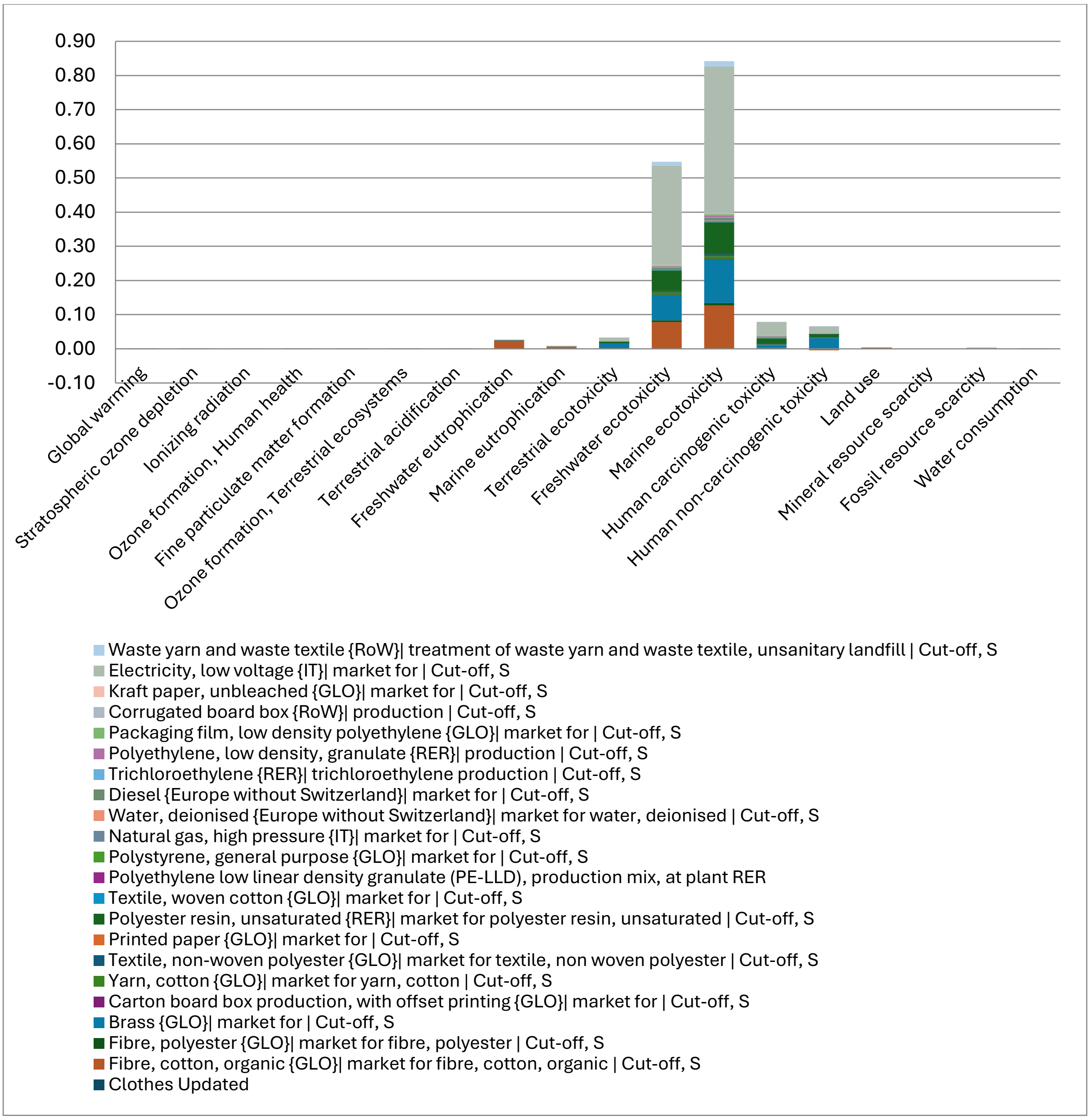


Figure 15: Illustration of impact assessment by Normalization Realized in MS Excel

Based on the normalized results, the focus is on nine main categories: Freshwater Eutrophication, Global Warming (kgCO_2), Stratospheric Ozone Depletion, Freshwater Ecotoxicity, Human Carcinogenic Toxicity, Human Non-Carcinogenic Toxicity, Marine Ecotoxicity, Marine Eutrophication and Water Consumption. The following sections provide a brief analysis of the main contributors in each impact category.

1. <u>Freshwater Eutrophication</u>:

Figure 16 illustrates that cotton fibre contributes 87.3% to freshwater eutrophication in the production of 1 kilogram of clothes. This high contribution is primarily linked to the agricultural practices involved in cotton cultivation. Cotton is one of the most water-intensive crops, and it's farming typically involves the extensive use of synthetic fertilizers rich in nitrogen and phosphorus to enhance growth and yield.

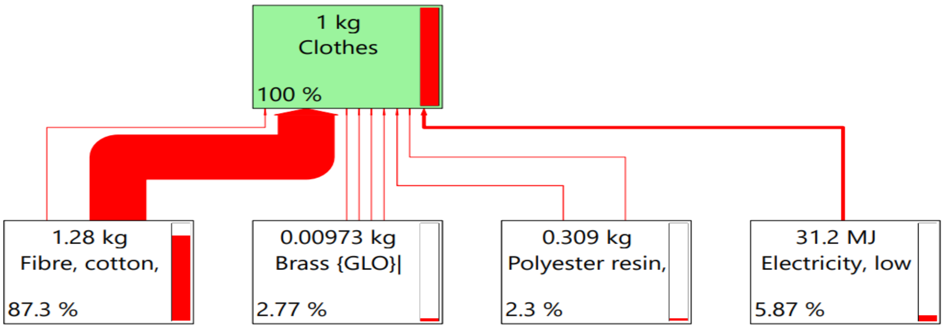


Figure 16: Illustration of inputs contribution related to freshwater Eutrophication

When these fertilizers are applied to cotton fields, a significant portion can be washed off by irrigation or rainfall into nearby water bodies. This runoff, rich in N and P, is a primary driver of freshwater eutrophication. The environmental impact is particularly severe in regions where cotton is grown intensively, such as in parts of India, the United States, and China, where large-scale monoculture practices exacerbate the runoff problem. Studies have shown that cotton farming can significantly contribute to nutrient pollution, leading to the degradation of freshwater ecosystems (Gautam & Tyagi, 2006)

Additionally, the environmental impact of cotton is compounded by the extensive use of pesticides and other agrochemicals, which further pollute water bodies and contribute to eutrophication. Efforts to mitigate these impacts include the promotion of organic cotton farming, which avoids synthetic fertilizers, and the adoption of precision agriculture techniques to optimize fertilizer use and minimize runoff (United Nations Environment Programme, 2011)

Contribution of Electricity:

Electricity contributes 5.87% to freshwater eutrophication in the production process. This impact is associated with the energy sources used to generate electricity. In regions where coal, biomass, or natural gas are predominant, the production of electricity can result in the release of nitrogen oxides (NOx) into the atmosphere. These pollutants eventually settle into water bodies through atmospheric deposition, contributing to nutrient enrichment and eutrophication.

Moreover, the cooling water used in thermoelectric power plants can carry pollutants back into freshwater systems, further exacerbating the problem. Renewable energy sources like hydropower can also contribute to eutrophication indirectly, as large reservoirs can promote the growth of algae due to changes in water flow and temperature. Therefore, the type of electricity generation and the environmental management practices in place significantly influence the extent of its contribution to freshwater eutrophication.

Contribution of Brass:

Brass production accounts for 2.77% of the impact on freshwater eutrophication. The environmental burden associated with brass largely stems from the mining and processing of copper and zinc, the primary metals in brass. Mining activities can cause significant soil and water disturbances, leading to the runoff of nutrients and other pollutants into water bodies.

During the ore processing and refining stages, wastewater discharge often contains residual chemicals, metals, and nutrients that contribute to eutrophication. Furthermore, the smelting and alloying processes emit nitrogen compounds that can further increase nutrient loads in freshwater systems. Effective management of mining waste and the adoption of cleaner production techniques are crucial in reducing the eutrophication potential of brass production.

Contribution of Polyester Resin:

Polyester resin contributes 2.3% to freshwater eutrophication. Polyester production is a petrochemical-intensive process, involving the polymerization of ethylene derived from oil or natural gas. The production process can lead to the discharge of nutrient-rich wastewater, especially if effluents from chemical plants are not adequately treated before being released into water bodies.

The contribution of polyester to eutrophication is relatively lower compared to cotton; however, it is significant due to the scale of polyester use in the textile industry. The adoption of closed-loop water systems and advanced wastewater treatment technologies can help mitigate the eutrophication potential associated with polyester production.

Discussion

The analysis of freshwater eutrophication in the production of 1 kilogram of clothes reveals that cotton fibre is the dominant contributor, primarily due to the extensive use of fertilizers in cotton agriculture. Electricity, brass, and polyester resin also contribute to eutrophication, albeit to a lesser extent. Addressing freshwater eutrophication in the textile industry requires a multifaceted approach, including the adoption of sustainable farming practices, cleaner production technologies, and more efficient water and nutrient management systems. These strategies are essential for reducing the environmental impact of textile production on freshwater ecosystems.

2. Global Warming (kg CO_2):

The Figure 17 illustrates the contributions of various inputs to global warming potential, measured in kilograms of CO_2 equivalent, during the production of 1 kilogram of clothing. The key contributors include cotton fibre, polyester resin, natural gas, diesel, polyethylene, electricity, and waste yarn.

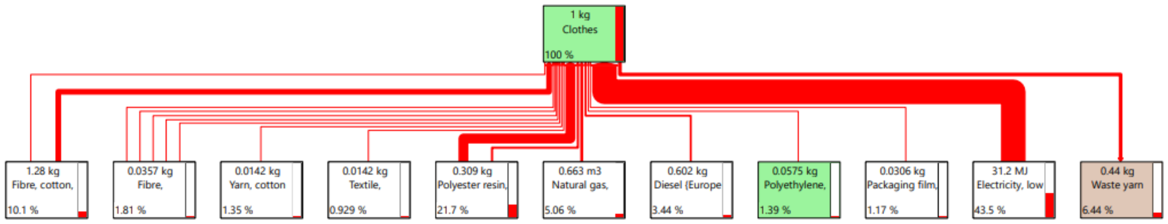


Figure 17: Illustration of inputs contribution related to global warming

Contribution of Electricity:

Electricity is the most significant contributor to global warming potential, accounting for 43.5% of the total impact. The high contribution from electricity is primarily due to the generation of electricity from fossil fuels, particularly coal, oil, and natural gas, which release large amounts of carbon dioxide (CO_2) and other greenhouse gases (GHGs) into the atmosphere. The carbon intensity of electricity production is a critical factor in the overall environmental footprint of textile manufacturing, making energy efficiency and the transition to renewable energy sources essential for reducing global warming impacts (International Energy Agency, 2019).

Contribution of Polyester Resin:

Polyester resin contributes 21.7% to the global warming potential. The production of polyester, a synthetic fibre derived from petrochemicals, is energy-intensive and involves the emission of significant amounts of CO_2 and other GHGs. The reliance on non-renewable fossil resources for polyester production exacerbates its carbon footprint, making it a major contributor to climate change. The impact of polyester highlights the environmental costs associated with synthetic textiles and the need for sustainable alternatives and recycling technologies (Shen, Worrell, & Patel, 2010).

Contribution of Cotton Fiber:

Cotton fibre, accounting for 10.1% of the global warming potential, is another significant contributor. Although cotton is a natural fibre, its cultivation is resource-intensive, particularly in terms of water and fertilizer use. The use of nitrogen-based fertilizers in cotton farming contributes to the release of nitrous oxide (N_2O), a potent greenhouse gas with a much higher global warming potential than CO_2. Additionally, the energy used in processing cotton into fibre further adds to its carbon footprint (Chapagain, Hoekstra, Savenije, & Gautam, 2006).

Contribution of Natural Gas and Diesel:

Natural gas and diesel contribute 5.06% and 3.44% to the global warming potential, respectively. The combustion of these fossil fuels for energy and transportation releases CO_2 and other GHGs, contributing directly to global warming. Natural gas, often considered a "cleaner" fossil fuel, still has a significant carbon footprint, particularly when considering methane emissions associated with its extraction and distribution.

Contribution of Polyethylene:

Polyethylene, used in packaging, contributes 1.39% to the global warming potential. The production of polyethylene involves the processing of ethylene, a petrochemical, which requires significant energy inputs and results in CO_2 emissions. While its contribution is smaller compared to other inputs, the widespread use of plastic packaging in the textile industry adds to the overall carbon footprint, highlighting the need for sustainable packaging solutions (Andrady, 2011).

Contribution of Waste Yarn:

Waste yarn contributes 6.44% to the global warming potential. The production and disposal of textile waste, including waste yarn, generate CO_2 and other GHGs. Improper disposal or incineration of textile waste can significantly increase its carbon footprint, underscoring the importance of waste management practices such as recycling and reusing textile materials to minimize environmental impact.

Contribution of Textile and Cotton Yarn:

Textiles and cotton yarn contribute 0.929% and 1.35% respectively to the global warming potential. These contributions reflect the energy-intensive processes involved in spinning and weaving, as well as the associated emissions from the machinery used in these processes. While their individual contributions are smaller, they add up across the global textile industry, making energy efficiency in these processes crucial for reducing the overall carbon footprint.

Discussion:

The analysis identifies electricity as the primary contributor to global warming potential in textile production, followed by polyester resin and cotton fibre. The significant impact of electricity highlights the environmental benefits of shifting to renewable energy sources, while the contributions of polyester and cotton underscore the challenges associated with both synthetic and natural fibres. Reducing the global warming potential of textile production will require a combination of energy efficiency improvements, sustainable material choices, and enhanced waste management practices to address the full lifecycle emissions associated with clothing production.

3. Stratospheric Ozone Depletion:

The Sankey diagram in Figure 18 provided highlights the contribution of various inputs to the stratospheric ozone depletion potential in the production of 1 kilogram of clothing. The key inputs analysed include organic cotton fibre, polyester resin, natural gas, diesel, electricity, and cotton yarn.

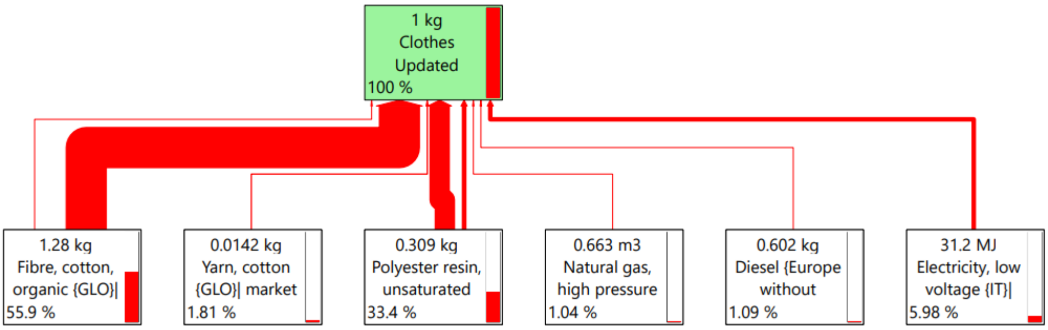


Figure 18: Illustration of inputs contribution related to ozone depletion

Contribution of Organic Cotton Fiber:

Organic cotton fibre is the most significant contributor to stratospheric ozone depletion, accounting for 55.9% of the total impact. Although organic cotton is often promoted for its reduced chemical input during cultivation, the agricultural processes associated with its production still involve the use of nitrogen-based fertilizers, which can release nitrous oxide (N2O). Nitrous oxide is a potent greenhouse gas and a significant ozone-depleting substance. Despite its organic label, the extensive land use and associated farming activities still pose a substantial impact on ozone depletion, especially in large-scale (Boucher & Friot, 2017).

Contribution of Polyester Resin:

Polyester resin, contributing 33.4%, is another major contributor to ozone depletion. The production of polyester involves chemical processes that can release substances such as volatile organic compounds (VOCs) and nitrous oxide, both of which have the potential to deplete the stratospheric ozone layer. As was the case for global warming, the significant impact here reflects the intensive nature of polyester production, which relies heavily on petrochemical inputs and energy, often from fossil fuels.

Contribution of Natural Gas and Diesel:

Natural gas and diesel contribute 1.04% and 1.09% to the ozone depletion potential, respectively. These contributions are mainly due to the combustion processes involved in their use, which release nitrogen oxides (NOx). Though their contributions are smaller relative to cotton and polyester, they are still notable, especially when considering the cumulative effects of widespread fossil fuel use across the industry.

Contribution of Electricity:

Electricity use contributes 5.98% of the total ozone depletion. The impact of electricity in this context largely depends on the energy mix of the electricity grid. Owing to the same reasons as global warming, the relatively high contribution here suggests that the electricity used in this production process likely comes from such sources.

Contribution of Cotton Yarn:

Cotton yarn, with a contribution of 1.81%, plays a smaller role in ozone depletion. However, its impact is still relevant, particularly when considering the cumulative effects across large-scale textile production. The energy and processes involved in spinning cotton into yarn, including the use of machinery powered by electricity and potentially fossil fuels, contribute to this percentage.

Discussion:

The analysis reveals that organic cotton fibre, despite being organic, is a significant contributor to stratospheric ozone depletion due to the agricultural practices associated with its cultivation. Polyester resin also plays a major role, underlining the environmental costs of synthetic textile production. Fossil fuel-derived energy sources such as natural gas, diesel, and electricity further exacerbate the problem, with their combustion products contributing to ozone layer degradation. The findings suggest that mitigating the ozone depletion potential of clothing production would require systemic changes, including the adoption of more sustainable agricultural practices, the development of greener chemical processes for synthetic fibres, and a transition to renewable energy sources.

4. Water Consumption:

Analysing Figure 19, the contribution of various inputs to water consumption in the production of 1 kilogram of clothing can be observed. The inputs analysed include cotton fibre, cotton yarn, woven textiles, polyester, polyethylene, packaging materials, and electricity.

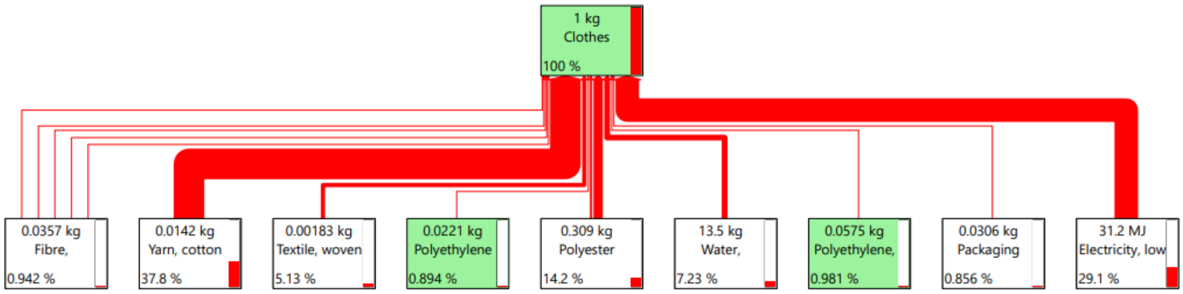


Figure 19: Illustration of inputs contribution related to water consumption

Contribution of Cotton Yarn:

Cotton yarn is the most significant contributor to water consumption, accounting for 37.8% of the total impact. The high usage of water is primarily due to the agricultural requirements of cotton cultivation. Cotton is known for being a water-intensive crop, requiring large amounts of water for irrigation throughout its growth cycle. This water consumption is particularly impactful in regions where water scarcity is an issue, leading to significant environmental and social challenges. The production of cotton yarn further amplifies water use due to processes like dyeing and finishing, which require substantial water resources.

Contribution of Electricity:

Electricity contributes 29.1% to water consumption. The water used in electricity production, especially when generated from fossil fuels or nuclear power, is significant. Water is often used for cooling purposes in power plants, and the consumption associated with these processes can be substantial. The impact of electricity on water consumption highlights the indirect effects of energy use in textile production.

Contribution of Polyester:

Polyester, contributing 14.2% to water consumption, is another significant factor. While polyester is a synthetic fibre that does not require agricultural water, its production involves water-intensive processes in the petrochemical industry. Water is used in various stages of polyester production, including cooling, chemical reactions, and purification processes. The environmental impact of polyester's water consumption is less visible than that of natural fibres but is significant nonetheless, especially given the scale of polyester use in the textile industry.

Contribution of Water Usage in Processing:

Direct water usage in the processing stage, accounting for 7.23%, also contributes to the total water consumption. This includes water used in the dyeing, washing, and finishing of textiles, which are essential steps in clothing production. The water-intensive nature of these processes can lead to significant water use, particularly in large-scale textile manufacturing operations. Efficient water management and the adoption of water-saving technologies are crucial to reducing this impact.

Contribution of Woven Textiles:

Woven textiles contribute 5.13% to water consumption. The production of woven fabrics involves multiple steps, including spinning, weaving, and dyeing, each of which requires water. The cumulative water use across these stages can be substantial, particularly when considering the global scale of textile production. Innovations in water-efficient weaving and dyeing processes could help mitigate this impact.

Contribution of Polyethylene and Packaging:

Polyethylene, used in packaging, contributes 0.981% to water consumption. Although the direct water use in the production of polyethylene is relatively low, the widespread use of plastic packaging in the textile industry amplifies its overall environmental impact. Packaging materials, including polyethylene and other plastics, play a role in the water footprint of textile products, particularly in terms of their production and disposal.

Contribution of Cotton Fiber:

Interestingly, cotton fibre itself contributes only 0.942% to direct water consumption in this specific analysis, which seems counterintuitive given cotton's well-known water demands. This could be due to the way water consumption is allocated across different stages of production, with a more significant portion attributed to the processing into yarn and textiles rather than the raw fibre alone. Nonetheless, the overall water footprint of cotton remains high, and reducing water use in cotton farming is critical for sustainability.

Discussion:

The analysis identifies cotton yarn and electricity as the primary contributors to water consumption in textile production, followed by polyester. The significant impact of cotton highlights the environmental challenges associated with water-intensive agricultural practices, while the contribution of electricity underscores the indirect water use associated with energy production. Polyester also plays a notable role, reflecting the water use in synthetic fibre production. The findings suggest that reducing water consumption in the textile industry will require a comprehensive approach, including improvements in agricultural practices, energy efficiency, and water management in processing stages.

5. Freshwater Ecotoxicity

Figure 20 illustrates the contributions of various inputs to freshwater ecotoxicity during the production of 1 kilogram of clothing. The primary inputs analysed include cotton fibre, carton, cotton yarn, textiles, brass, polyester, trichloroethylene, polyethylene, corrugated board, natural gas, diesel, water, waste yarn, and electricity.

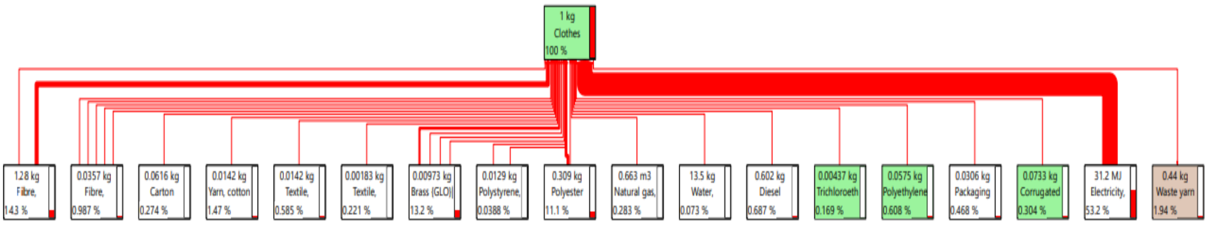


Figure 20: Illustration of inputs contribution related to Freshwater Ecotoxicity

Contribution of Electricity:

Electricity is the most significant contributor to freshwater ecotoxicity, accounting for 53.2% of the total impact. The generation of electricity, particularly from fossil fuels like coal, oil, and natural gas, releases a variety of pollutants, including heavy metals (such as mercury and lead) and other toxic substances. These pollutants can be deposited into freshwater systems through atmospheric deposition and runoff, leading to severe ecotoxicological impacts on aquatic life.

Contribution of Brass:

Brass is the second-largest contributor, accounting for 13.2% of the freshwater ecotoxicity impact. The production of brass involves the extraction and processing of copper and zinc, which can release toxic metals into the environment. These metals can accumulate in freshwater ecosystems, posing significant risks to aquatic organisms and disrupting ecological balance. The impact of brass highlights the environmental cost of metal production and the importance of sustainable sourcing and waste management in reducing ecotoxicity (Norgate & Rankin, 2000).

Contribution of Polyester:

Polyester contributes 11.1% to freshwater ecotoxicity. Polyester production involves petrochemical processes that release a range of pollutants, including organic chemicals and heavy metals, which can contaminate freshwater systems. Additionally, the degradation of polyester products can result in microplastic pollution, further contributing to the ecotoxicity of water bodies. Polyester's impact reiterates the needs outlined for global warming.

Contribution of Cotton Fiber:

Cotton fibre contributes 4.3% to freshwater ecotoxicity. Although cotton is a natural fibre, its cultivation typically involves the extensive use of pesticides and fertilizers. These chemicals can run off into freshwater systems, causing toxicity to aquatic life.

Contribution of Trichloroethylene:

Trichloroethylene, a chlorinated solvent used in various industrial processes, contributes 10.6% to freshwater ecotoxicity. Trichloroethylene is highly toxic to aquatic organisms, and its release into water bodies can lead to severe ecological damage. The significant impact of trichloroethylene highlights the need for safer alternatives and stricter control measures to prevent its release into the environment (Andrady, 2011).

Contribution of Natural Gas and Diesel:

Natural gas and diesel contribute 2.8% and 8.7% respectively to freshwater ecotoxicity. The extraction, processing, and combustion of these fossil fuels release a variety of pollutants, including hydrocarbons, sulphur compounds, and heavy metals, which can enter freshwater systems through runoff or atmospheric deposition. These pollutants can have harmful effects on aquatic organisms, contributing to the overall ecotoxicity of freshwater environments.

Contribution of Polyethylene and Packaging:

Polyethylene, used in packaging, contributes 5.08% to freshwater ecotoxicity. The production and disposal of polyethylene involve the release of chemicals and microplastics that can pollute freshwater systems. Microplastics, in particular, pose a growing concern due to their persistence in the environment and potential to cause long-term ecological harm trichloroethylene.

Contribution of Waste Yarn:

Waste yarn contributes 1.9% to freshwater ecotoxicity. The disposal or treatment of textile waste, including yarn, can lead to the release of dyes, chemicals, and microfibers into freshwater systems. These substances can be toxic to aquatic organisms, adding to the ecotoxicity impact of textile production. Proper waste management practices are essential to minimize the environmental impact of textile waste.

Discussion:

The analysis identifies electricity as the primary contributor to freshwater ecotoxicity in textile production, followed by brass, polyester, and trichloroethylene. The significant impact of electricity underscores the environmental benefits of shifting to renewable energy sources. Brass and polyester also contribute notably to ecotoxicity, reflecting the environmental costs associated with metal production and synthetic fibre use. The contribution of cotton fibre highlights the ongoing challenges in reducing the environmental impact of agricultural practices. Overall, this assessment emphasizes the need for cleaner production processes, safer materials, and improved waste management, to reduce the freshwater ecotoxicity associated with textile manufacturing.

6. Human Carcinogenic Toxicity

Figure 21 illustrates the contributions of various inputs to human carcinogenic toxicity in the production of 1 kilogram of clothing. The primary inputs analysed include cotton fibre, cotton yarn, textiles, brass, polyester, polyethylene, diesel, natural gas, and electricity.

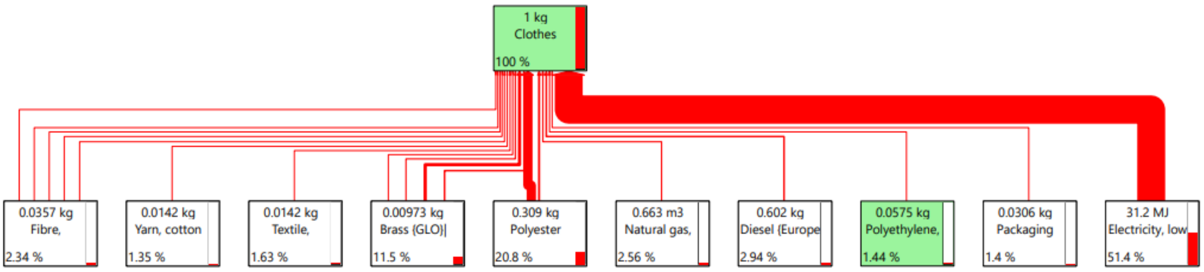


Figure 21: Illustration of inputs contribution related to Human Carcinogenic Toxicity

Contribution of Electricity:

Electricity is the most significant contributor to human carcinogenic toxicity, accounting for 51.4% of the total impact. The production of electricity, particularly when sourced from fossil fuels such as coal, oil, and natural gas, involves the emission of carcinogenic pollutants, including particulate matter (PM), polycyclic aromatic hydrocarbons (PAHs), and heavy metals such as mercury. These pollutants pose significant health risks, contributing to respiratory diseases, lung cancer, and other carcinogenic effects in populations exposed to them.

Contribution of Polyester:

Polyester contributes 20.8% to human carcinogenic toxicity. This can be attributed to reasons much similar to those discussed in the impact categories of global warming and stratospheric ozone depletion.

Contribution of Brass:

Brass accounts for 11.5% of the human carcinogenic toxicity impact. The production of brass involves the extraction and processing of copper and zinc, which can lead to the release of carcinogenic metals and compounds, including arsenic and cadmium. These substances can contaminate air, water, and soil, posing significant health risks through exposure and ingestion. The processing of brass, especially in the presence of high temperatures, can further exacerbate the release of carcinogenic fumes, contributing to occupational hazards and broader environmental impacts. Similar impacts of brass could also be seen earlier when discussing freshwater ecotoxicity.

Contribution of Natural Gas and Diesel:

Natural gas and diesel contribute 2.56% and 2.94%, respectively, to human carcinogenic toxicity. The combustion of these fossil fuels releases a range of carcinogenic pollutants, including benzene, formaldehyde, and particulate matter. These emissions contribute to air pollution, which is directly linked to increased cancer risks, particularly lung cancer.

Contribution of Polyethylene and Packaging:

Polyethylene, used primarily in packaging, contributes 1.44% to human carcinogenic toxicity. The production of polyethylene involves the processing of ethylene, a petrochemical, which can release carcinogenic byproducts such as benzene and 1,3-butadiene. Although its contribution is smaller compared to other inputs, the widespread use of polyethylene in packaging across industries amplifies its overall impact.

Contribution of Cotton Fiber, Yarn, and Textiles:

Cotton fibre, yarn, and textiles contribute 2.34%, 1.35%, and 1.63%, respectively, to human carcinogenic toxicity. As also discussed in the freshwater ecotoxicity and global warming categories, the agricultural practices associated with cotton farming, including the use of pesticides and herbicides, are significant sources of carcinogenic compounds. These chemicals can enter the food chain and water supply, posing long-term health risks to populations in agricultural regions.

Discussion:

The analysis identifies electricity and polyester as the primary contributors to human carcinogenic toxicity in the production of clothing. The significant impact of electricity highlights the health risks associated with fossil fuel-based energy production, while the contribution of polyester underscores the challenges posed by synthetic textiles. Brass also plays a notable role due to the carcinogenic risks associated with metal processing. The contributions of natural gas, diesel, and polyethylene reflect the broader environmental and health challenges posed by the reliance on fossil fuels and petrochemicals in the textile industry. Mitigating these impacts requires a comprehensive approach, including the adoption of cleaner energy sources, safer materials, and improved chemical management practices throughout the supply chain.

7. Human Non-Carcinogenic Toxicity

Figure 22 represents the contributions of various inputs to human non-carcinogenic toxicity during the production of 1 kilogram of clothing. The inputs considered include cotton fibre, cotton yarn, textiles, brass, polyester, polyethylene, diesel, waste yarn, and electricity.

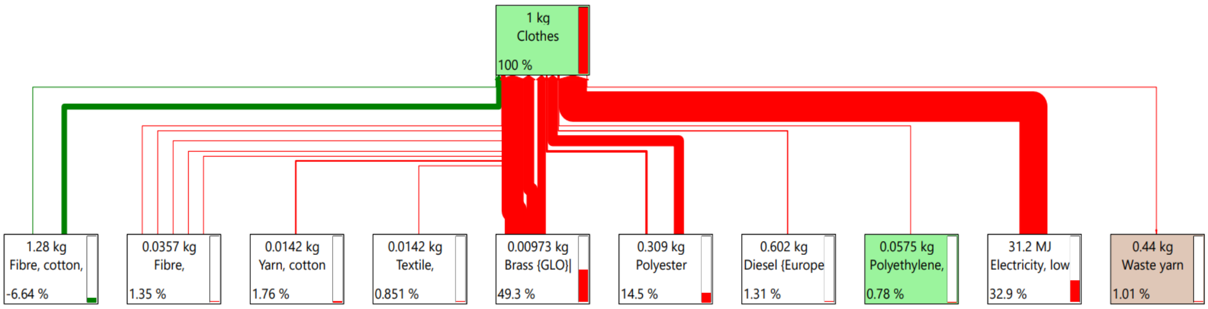


Figure 22: Illustration of inputs contribution related to Human Carcinogenic Toxicity

Contribution of Brass:

Brass is the most significant contributor to human non-carcinogenic toxicity, accounting for 49.3% of the total impact. This high contribution is primarily due to the presence of heavy metals such as copper and zinc in brass. Much similar to the case of freshwater ecotoxicity, during the production and processing of brass, these metals can be released into the environment, leading to potential exposure risks through air, water, and soil contamination.

Contribution of Electricity:

Electricity usage contributes 32.9% to human non-carcinogenic toxicity. The production of electricity, particularly when derived from fossil fuels, can result in the emission of pollutants such as sulphur dioxide (SO2), nitrogen oxides (NOx), and particulate matter (PM). These pollutants are associated with respiratory and cardiovascular diseases, and they contribute significantly to non-carcinogenic health risks in populations exposed to them. The large contribution from electricity reflects the reliance on energy-intensive processes in textile manufacturing and the environmental impacts of conventional energy sources.

Contribution of Polyester:

Polyester accounts for 14.5% of the human non-carcinogenic toxicity impact. The production of polyester involves the use of petrochemicals and various chemical additives that can be harmful to human health. Exposure to these chemicals during the manufacturing process or through environmental contamination can lead to a range of non-carcinogenic health effects, including skin irritation, respiratory issues, and endocrine disruption.

Contribution of Cotton Fiber:

Interestingly, cotton fibre shows a negative contribution of -6.64%, which may indicate a net beneficial effect in this specific context, possibly due to the reduced use of harmful chemicals in organic cotton farming. Organic cotton production generally avoids synthetic pesticides and fertilizers, which are significant contributors to human toxicity. This result suggests that organic cotton may have a lower non-carcinogenic toxicity impact compared to conventionally farmed cotton, although the overall environmental footprint of cotton cultivation remains significant based on other available impact categories.

Contribution of Polyethylene and Diesel:

Polyethylene and diesel contribute 0.78% and 1.31% respectively to human non-carcinogenic toxicity. Polyethylene, used in packaging, is a plastic derived from petrochemicals, and its production can involve the release of harmful chemicals. Diesel combustion releases various pollutants, including particulate matter and nitrogen oxides, which are known to contribute to respiratory and cardiovascular diseases.

Contribution of Waste Yarn:

Waste yarn contributes 1.01% to the human non-carcinogenic toxicity impact. The disposal or recycling of textile waste can involve exposure to chemicals used in dyeing and finishing processes, which may include substances that are harmful to human health. Proper management of textile waste is therefore essential to minimize its impact on human non-carcinogenic toxicity.

Discussion:

The analysis identifies brass and electricity as the primary contributors to human non-carcinogenic toxicity in textile production. The significant impact of brass highlights the risks associated with heavy metal exposure, while the large contribution from electricity reflects the health impacts of air pollutants generated during energy production. Polyester also plays a notable role, emphasizing the need for safer alternatives in synthetic fibre production. The negative impact of organic cotton suggests potential health benefits from reducing the use of harmful chemicals in agriculture. Overall, this assessment points to the importance of reducing the environmental and health impacts of textile manufacturing through cleaner production processes, safer materials, and sustainable energy sources.

8. Marine Ecotoxicity

Figure 23 illustrates the contribution of various inputs to marine ecotoxicity in the production of 1 kilogram of clothing. The inputs considered include cotton fibre, carton, cotton yarn, textiles, brass, polyester, trichloroethylene, polyethylene, corrugated board, natural gas, diesel, water, waste yarn, and electricity.

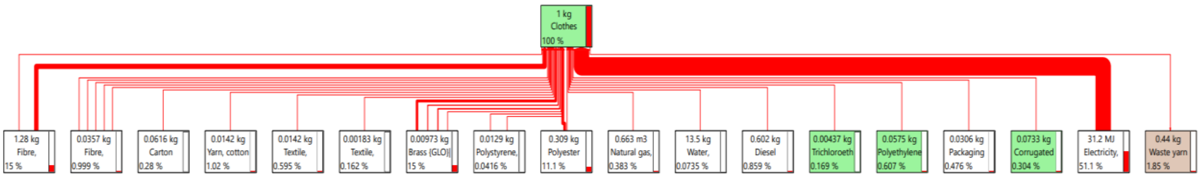


Figure 23: Illustration of inputs contribution related to Marine Ecotoxicity

Contribution of Electricity:

Electricity is the most significant contributor to marine ecotoxicity, accounting for 51.1% of the total impact. This large contribution is likely due to the generation of electricity from fossil fuels, such as coal, oil, and natural gas, which involves the emission of heavy metals and other toxic substances. These pollutants can enter water bodies through atmospheric deposition or runoff, leading to adverse effects on marine life.

Contribution of Cotton Fiber:

Cotton fibre contributes 15.5% to marine ecotoxicity, reflecting the environmental impact of cotton cultivation and processing. Cotton farming often involves the use of pesticides and fertilizers, which can run off into water bodies, leading to the accumulation of toxic substances in marine ecosystems. These chemicals can be highly detrimental to aquatic organisms, causing toxicity that affects biodiversity and ecosystem.

Contribution of Brass:

Brass, contributing 5% to marine ecotoxicity, is another significant input due to the environmental impact of its production. Brass production involves the extraction and processing of copper and zinc, both of which are metals that can be toxic to marine organisms. The release of these metals into water bodies during manufacturing or through waste can lead to long-term environmental damage, making brass a noteworthy contributor to marine ecotoxicity.

Contribution of Polyester:

Polyester accounts for 11.1% of the marine ecotoxicity impact. Polyester production involves the use of petrochemicals and energy-intensive processes that can release pollutants into the environment. The disposal and degradation of polyester also contribute to microplastic pollution, which is a growing concern in marine environments. Microplastics can also absorb and concentrate toxic substances, further exacerbating their impact on marine life (Shen, Worrell, & Patel, 2010)

Contribution of Trichloroethylene and Polyethylene:

Trichloroethylene and polyethylene contribute 16.9% and 5.07%, respectively, to marine ecotoxicity. Trichloroethylene, a chlorinated solvent used in industrial processes, is highly toxic to aquatic life and can cause significant harm when released into water bodies. Polyethylene, while less toxic than trichloroethylene, contributes to plastic pollution in marine environments. The accumulation of plastic debris can lead to physical harm to marine organisms and the release of toxic additives over time.

Contribution of Natural Gas and Diesel:

Natural gas and diesel contribute 3.83% and 8.59%, respectively, to marine ecotoxicity. The extraction, processing, and combustion of these fossil fuels release pollutants, including hydrocarbons and heavy metals, into the environment. These pollutants can find their way into marine ecosystems, causing toxicity that affects a wide range of aquatic organisms.

Contribution of Waste Yarn:

Waste yarn contributes 1.85% to marine ecotoxicity, reflecting the impact of textile waste. Improper disposal or treatment of textile waste can lead to the release of dyes, chemicals, and microfibers into water bodies. These substances can be toxic to marine life, contributing to the overall ecotoxicity impact of textile production.

Contribution of Corrugated Board and Carton:

Corrugated board and carton contribute 3.04% and 2.95%, respectively, to marine ecotoxicity. These packaging materials, while primarily made from paper, can contain adhesives, inks, and coatings that may leach toxic substances into water bodies if not properly managed. Although their contribution is lower than other inputs, they still represent a potential source of marine pollution.

Discussion:

The analysis identifies electricity, cotton fibre, and polyester as significant contributors to marine ecotoxicity in textile production. The impact of electricity underscores the importance of transitioning to renewable energy sources to reduce the environmental burden of the industry. The contributions of cotton fibre and polyester highlight the challenges associated with both natural and synthetic fibres, particularly in terms of pesticide use, chemical pollution, and plastic waste. Trichloroethylene and polyethylene also play important roles, emphasizing the need for safer chemical alternatives and improved waste management practices to mitigate marine ecotoxicity.

9. Marine Eutrophication

Figure 24 indicates the contribution of various inputs to marine eutrophication during the production of 1 kilogram of clothing. The key inputs include organic cotton fibre, cotton yarn, woven cotton textiles, polyester resin, and electricity.

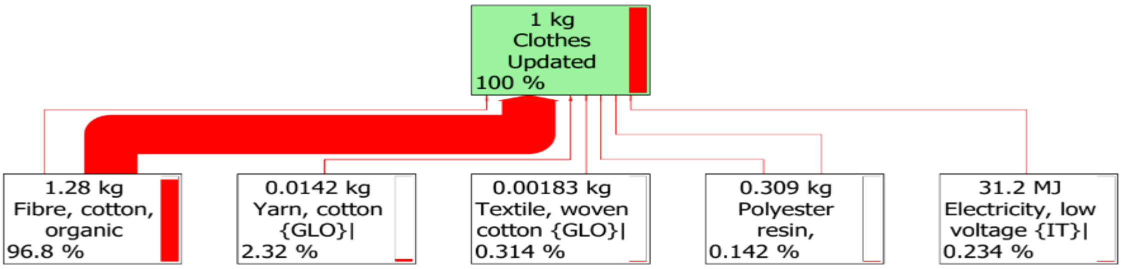


Figure 24: Illustration of inputs contribution related to Marine Eutrophication

Contribution of Organic Cotton Fiber:

Organic cotton fibre is the predominant contributor to marine eutrophication, accounting for a significant 96.8% of the total impact. The high contribution of organic cotton is largely due to the agricultural practices involved in its cultivation. Despite being organic, cotton farming requires substantial inputs, particularly in the form of organic fertilizers. These fertilizers, when leached into water bodies, can lead to nutrient overloads, causing eutrophication, which is the excessive growth of algae and aquatic plants. This process depletes oxygen levels in water bodies, leading to the death of marine life and the disruption of aquatic ecosystems

Contribution of Cotton Yarn:

Cotton yarn, contributing 2.32% to marine eutrophication, also has a notable impact. The production of cotton yarn involves the spinning of cotton fibres, a process that, while less intensive than agriculture, still contributes to nutrient runoff and water pollution. The cumulative effect of cotton yarn production across the textile industry contributes to the overall eutrophication impact, though to a lesser extent than raw cotton cultivation.

Contribution of Woven Cotton Textiles:

Woven cotton textiles contribute 0.314% to marine eutrophication. The weaving process itself is not a major direct contributor to nutrient runoff; however, the processing of cotton into woven textiles involves various stages that can indirectly contribute to water pollution. These include washing and finishing processes that may release chemicals and nutrients into water bodies if not properly managed.

Contribution of Polyester Resin:

Polyester resin accounts for 0.142% of the marine eutrophication impact. As a synthetic material, polyester does not contribute directly to nutrient runoff in the same way that agricultural products do. However, the production of polyester involves the use of petrochemicals, and the associated industrial processes can contribute to water pollution through the discharge of untreated or partially treated wastewater, which can carry nutrients and other pollutants into marine environments.

Contribution of Electricity:

Electricity, with a contribution of 0.234%, has the smallest impact on marine eutrophication among the inputs listed. The generation of electricity, especially from fossil fuels, can lead to emissions that indirectly affect water bodies. For example, nitrogen oxides (NOx) released during fossil fuel combustion can deposit into water bodies through atmospheric deposition, contributing to nutrient enrichment.

Discussion:

The analysis clearly identifies organic cotton fibre as the primary contributor to marine eutrophication in the production of 1 kilogram of clothing. This underscores the significant environmental challenges associated with cotton farming, even when organic methods are employed. The impact of cotton yarn and woven textiles, while lower, also reflects the broader environmental footprint of cotton-based products. Polyester resin and electricity contribute minimally to marine eutrophication, highlighting the differing environmental impacts of synthetic versus natural fibres. To mitigate marine eutrophication, strategies should focus on improving agricultural practices, particularly in cotton cultivation, to reduce nutrient runoff and enhance water management in textile processing.

4.4 Interpretation

This OLCA unveils environmental impact hotspots within clothing production that electricity generation is the primary environmental burden across multiple impact categories, contributing 51.4% to human carcinogenic toxicity, 51.1% to marine ecotoxicity, and 43.5% to global warming. Cotton fibre significantly influences freshwater eutrophication (87.3%) and water consumption (37.8%) However, cotton yarn derived from this externally sourced cotton still significantly contributes, driven by fertilizer runoff and irrigation needs. Polyester is notable for its contributions to ozone depletion (33.4%), carcinogenic toxicity (20.8%), and marine ecotoxicity (11.1%), reflecting the environmental costs of its production. Brass notably impacts human non-carcinogenic health (49.3%) and marine ecotoxicity (15%) due to toxic metal emissions. The substantial influence of organic cotton on marine eutrophication (96.8%) underscores the need for improved nutrient management in organic farming.

To address these environmental impacts, several sustainable practices may be recommended. Shifting to renewable energy sources can greatly reduce the environmental burden from electricity generation. Adopting water-efficient irrigation systems and sustainable fertilizer management in cotton production will help mitigate freshwater eutrophication and reduce water consumption. For polyester, it is suggested to enhance recycling technologies and explore eco-friendly alternatives to lower its environmental impact. In brass production, implementing cleaner production methods and effective emission controls can minimize toxic metal emissions. Additionally, collaborating with suppliers to improve nutrient management in organic farming can help address marine eutrophication issues. By integrating these strategies, the firm can significantly diminish its environmental burdens and strengthen its sustainability profile.

4.4.1 Improvement Suggestions

Owing to the recency of the OLCA methodology, there is not much existing work particularly discussing the environmental impacts of an organization as a whole. However, several LCA studies have been conducted on different apparel products including those from academics, as well as corporations such as Levi Strauss and Co., Nike, H&M and Zara. Thus, based on such pieces of literature, and taking into consideration the conducted assessment, a few possibilities have been suggested ahead that would help to achieve reduced amounts of emissions, leading to improved environmental performance. These reduced environmental impacts have been estimated based on the aforementioned sources. The quantitative analysis has been presented in tabular form as well to represent the current amounts of emissions and those that can be achieved following the given suggestions.

1. **Reduction in Carbon Footprint:**

   Currently, the Electricity is being purchased from the national grid, the production of which has a contribution of 43.5% in the Global Warming. As per our assessment, however, if the company transitions to using renewable energy resources, a reduction of around 30% can be achieved in the current contribution, resulting in new contribution of approximately 30.5%; much similar to the analysis presented by Peng, et al., (2022).

2. **Decrease in Water Consumption and Eutrophication:**

   As also assessed by Baydar, et al., (2015)The principal contributor to freshwater eutrophication and to water consumption is cotton, contributing 87.3% and 37.8%, respectively. Results suggest that implementing water-efficient irrigation and sustainable fertilizer practices can reduce these figures by an estimated 40%. This would bring freshwater eutrophication down to about 52.4% and water consumption to 22.7%.

3. Reduction in Environmental Impact from Polyester:

Polyester contributes 33.4% to ozone depletion, 20.8% to carcinogenic toxicity, and 11.1% to marine ecotoxicity. It is anticipated that advancing recycling technologies and using eco-friendly alternatives can reduce these impacts by around 35%. This could lower contributions to ozone depletion to 21.7%, carcinogenic toxicity to 13.5%, and marine ecotoxicity to 7.2% (Muthu, 2015).

4. Minimization of Toxic Emissions from Brass Production:

Brass impacts human non-carcinogenic health by 49.3% and marine ecotoxicity by 15%. If cleaner production techniques and efficient emission controls are used, these impacts could be reduced by approximately 30%. This would result in human non-carcinogenic health impacts reducing to 34.5% and marine ecotoxicity to 10.5%.

5. Improved Nutrient Management in Organic Farming:

Finally, organic cotton has a contribution of 96.8% to marine eutrophication. It is possible that improved nutrient management could reduce this by an estimated 40%, bringing the contribution down to about 58.1%.

These anticipated improvements can lead to substantial reductions in environmental impacts through the adoption of the proposed sustainable practices as shown in Table 7. They highlight the potential improvements in various categories by effectively addressing the current hotspots in the production processes.

Table 7: Anticipated impacts' reduction after applying the recommended practices

Impact Category	Current Contribution	Expected Reduction	New Contribution
Global Warming (Electricity)	43.5%	30%	~30.5%
Freshwater Eutrophication (Cotton)	87.3%	40%	~52.4%
Water Consumption (Cotton)	37.8%	40%	~22.7%
Ozone Depletion (Polyester)	33.4%	35%	~21.7%
Carcinogenic Toxicity (Polyester)	20.8%	35%	~13.5%
Marine Ecotoxicity (Polyester)	11.1%	35%	~7.2%

Impact Category	Current Contribution	Expected Reduction	New Contribution
Human Non-Carcinogenic Health (Brass)	49.3%	30%	~34.5%
Marine Ecotoxicity (Brass)	15%	30%	~10.5%
Marine Eutrophication (Organic Cotton)	96.8%	40%	~58.1%

4.4.2 In Terms of GHG Emissions

Understanding Greenhouse Gas (GHG) emissions in terms of Scope 1, Scope 2, and Scope 3 emissions is essential for comprehensive GHG accounting and reporting; Table 8 illustrates a breakdown based on the inputs and outputs provided:

Scope 1 (Direct Emissions): Include emissions from sources directly owned by the firm, such as those from burning purchased diesel which is (0.29 kg CO_2) and natural gas (0.42 kg CO_2) for the boiler system. This also covers emissions from the firm's production activities, including exhaust from company-owned vehicles and on-site fuel combustion.

Scope 2 (Indirect Emissions from Energy): Emissions from the generation of purchased electricity Emissions from the electricity which is (3.68 kg CO_2) purchased from the grid and consumed by the company.

Scope 3 (Other Indirect Emissions):

Scope 3 emissions are generated from the environmental impacts of outsourced inputs, focusing on their contributions to GHG emissions. These Scope 3 emissions cover the entire life cycle of production, processing, and transportation of materials such as polyester fibre, cotton, brass, printed paper, polyester resin, non-woven polyester textile, and polyethylene granulate. They also include emissions from water supply, waste textile management, and indirect activities like business travel, waste disposal, and employee commuting, which are not captured in Scope 1 or Scope 2.

Table 8 illustrates the GHG emissions for each input used along with identifying the scopes of the emissions. Furthermore, these emission categories have been represented in relation to the activities that cause them in Figure 25 while Figure 26 illustrates the percentage share of each type of scope of activity.

Table 8: Illustration of GHG emissions of Inputs in terms of (kg CO_2)

Element	**Global Warming (kg CO_2)**	**Scope**
Fibre, cotton, organic {GLO}| market for fibre, cotton, organic | Cut-off, S	0.86	3
Fibre, polyester {GLO}| market for fibre, polyester | Cut-off, S	0.15	3
Brass {GLO}| market for | Cut-off, S	0.04	3
Carton board box production, with offset printing {GLO}| market for | Cut-off, S	0.04	3
Yarn, cotton {GLO}| market for yarn, cotton | Cut-off, S	0.11	3
Textile, non-woven polyester {GLO}| market for textile, non-woven polyester | Cut-off, S	0.08	3
Printed paper {GLO}| market for | Cut-off, S	0.01	3
Polyester resin, unsaturated {RER}| market for polyester resin, unsaturated | Cut-off, S	1.83	3
Textile, woven cotton {GLO}| market for | Cut-off, S	0.02	3
Polyethylene low linear density granulate (PE-LLD), production mix, at plant RER	0.16	3
Polystyrene, general purpose {GLO}| market for | Cut-off, S	0.05	3
Natural gas, high pressure {IT}| market for | Cut-off, S	0.43	1
Water, deionised {Europe without Switzerland} | market for water, deionised | Cut-off, S	0.01	3

Element	**Global Warming (kg CO_2)**	**Scope**
Diesel {Europe without Switzerland} | market for | Cut-off, S	0.29	1
Trichloroethylene {RER}| trichloroethylene production | Cut-off, S	0.01	3
Packaging film, low density polyethylene {GLO}| market for | Cut-off, S	0.10	3
Corrugated board box {RoW}| production | Cut-off, S	0.04	3
Kraft paper, unbleached {GLO}| market for | Cut-off, S	$1.5\text{x}10^{-3}$	3
Electricity, low voltage {IT}| market for | Cut-off, S	3.68	2
Waste yarn and waste textile {RoW}| treatment of waste yarn and waste textile, unsanitary landfill | Cut-off, S	0.55	3
Total	**8.46 kg CO_2**	

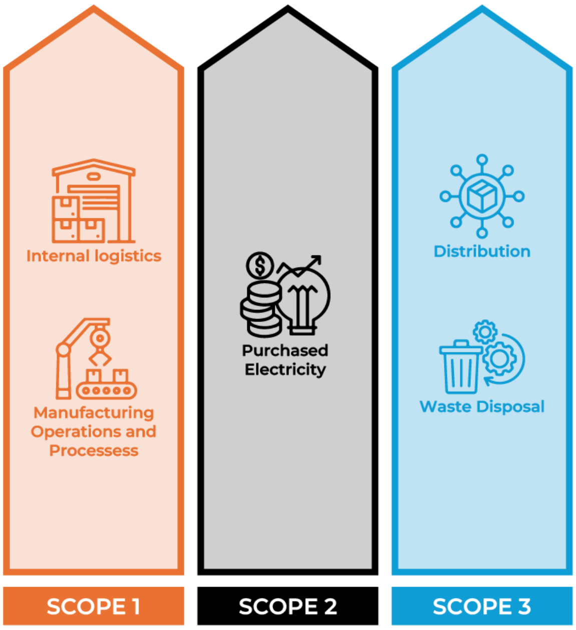


Figure 25: Activities related to Scope 1, 2 and 3 emissions

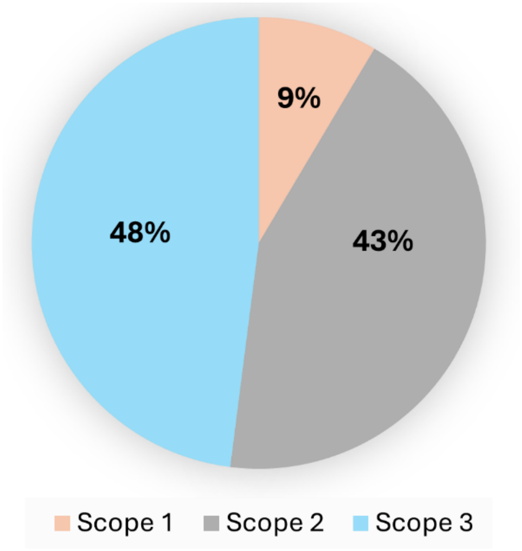


Figure 26: Percentage share of each scope in GHG emissions

5. CONCLUSION

The substantial environmental impacts generated from the fashion industry make necessary a transition towards sustainable practices. The OLCA methodology, as applied and presented in this thesis, serves as a powerful tool for quantifying and analyzing these impacts at an organizational level, enabling companies to identify and address their environmental hotspots throughout their value chains. The case study of the apparel manufacturing organization in Italy outlines a few of the critical areas where the industry must focus its sustainability efforts. The findings revealed that electricity generation, cotton production, polyester, and brass are major contributors to the company's environmental footprint, impacting various categories like global warming, water consumption, and ecotoxicity.

The case study's findings resonate with the environmental challenges highlighted in the previous sections of this thesis and align with reviewed literature such as the paper by Chapagain, et al, (2006) and the report conducted by Roos, et al., (2016)., particularly concerning the fashion industry's substantial water footprint and the environmental implications of material choices. The dominance of cotton fiber in contributing to freshwater eutrophication and water consumption aligns with the emphasis on the water-intensive nature of cotton production. The significant impact of polyester on ozone depletion, carcinogenic toxicity, and marine ecotoxicity reinforces the concerns raised about the environmental costs associated with synthetic materials. Identification of brass as a contributor to human non-carcinogenic health and marine ecotoxicity further supports the existing discussions on the potential harm posed by toxic metal emissions during material production. The substantial influence of organic cotton on marine eutrophication reiterates the need for improved nutrient management in organic farming. Moreover, findings on the significant contribution of electricity generation to various impact categories, particularly global warming, align with the reviewed literature's emphasis on the fashion industry's reliance on fossil fuels and the resulting greenhouse gas emissions.

In essence, the case study's results validate and reinforce the environmental concerns highlighted in the reviewed literature, providing concrete evidence of their manifestation in a real-world apparel manufacturing context. The findings also contribute to the growing body of knowledge on the environmental impacts of the fashion industry, offering valuable insights for researchers, policymakers, and industry stakeholders working towards a more sustainable future.

The dominance of electricity in multiple impact categories highlights the urgent need for transitioning to renewable energy sources rather than purchasing conventionally generated electricity from national grids. The substantial influence of the production of organic cotton on water consumption and eutrophication emphasize the necessity for adopting water-efficient irrigation systems and sustainable fertilizer management practices. The significant contributions of polyester and brass to various impact categories underscore the importance of exploring eco-friendly alternatives, enhancing recycling technologies, and implementing cleaner production methods.

The insights gained from this research present the opportunity for future research into environmentally sustainable solutions within the fashion industry. Further research could explore the environmental implications of various textile materials in more depth, including emerging sustainable alternatives and their potential for reducing environmental burdens. The exploration of innovative production technologies such as 3D printing and closed-loop systems, can also contribute to minimizing waste and resource consumption. Additionally, understanding consumer behavior and its role in promoting sustainability can lead to effective strategies for encouraging responsible consumption patterns. The development of comprehensive sustainability metrics and standardized reporting frameworks can further enhance transparency and accountability across the industry, enabling consumers and stakeholders to make informed choices. By embracing sustainable practices, fostering innovation, and engaging in collaborative efforts, the fashion industry can move towards a more environmentally responsible future, ensuring a balance between economic growth and ecological well-being.

FIGURES

TABLES

REFERENCES

Acero, A. P., Rodríguez, C., & Ciroth, A. (2015). *LCIA methods Impact assessment methods in Life Cycle Assessment and their impact categories.* Green Delta.

Alizadeh, L., Liscio, M. C., & Sospiro, P. (2024). The phenomenon of greenwashing in the fashion industry: A conceptual framework. *Sustainable Chemistry and Pharmacy, 37*.

Andersson, K., Brynolf, S., Landquist, H., & Svensson, E. (2016). Methods and Tools for Environmental Assessment. In K. Andersson, S. Brynolf, J. F. Lindgren, & M. Wilewska-Bien (Eds.), *Shipping and the Environment: Improving Environmental Performance in Marine Transportation* (pp. 265-289). Springer.

Andrady, A. L. (2011). Microplastics in the marine environment. *Marine pollution bulletin, 62*(8), 1596-1605.

Baker, K., & McNeill, L. S. (2023). A five-stage framework for sustainability certification for fashion brands: Can a standardised approach work in the fashion industry? *International Journal of Fashion Design, Technology and Education*, 1-15.

Baumann, H., & Cowell, S. J. (1999). An Evaluative Framework for Conceptual and Analytical Approaches Used in Environemental Management. *Greener Management International, 26*, 109-122.

Baydar, G., Ciliz, N., & Mammadov, a. A. (2015). Life cycle assessment of cotton textile products in Turkey. *Resources, Conservation and Recycling, 104*, 213-223.

Bjørn, A., Bey, N., Georg, S., Røpke, I., & Hauschild, M. Z. (2017). Is Earth recognized as a finite system in corporate responsibility reporting? *Journal of Cleaner Production, 163*, 106-117.

Bluesign. (n.d.). *YOUR PARTNER IN RESPONSIBLE AND MORE SUSTAINABLE TEXTILES*. Retrieved July 15, 2024, from https://www.bluesign.com/en/

Boucher, J., & Friot, D. (2017). *Primary microplastics in the oceans: a global evaluation of sources.* IUCN, Switzerland.

Brightest, Inc. (2024). *How to Measure Sustainabilty: A step-by-step definition of sustainability measurement, and how-to guide for selecting the right measurement framework (and metrics) for your organization*. Retrieved July 20, 2024, from https://www.brightest.io/sustainability-measurement

Brunner, P. H., & Rechberger, H. (2003). *Practical Handbook of Material Flow Analysis.* Florida: Lewis Publishers, CRC Press LLC.

Bueno, N., Bernaz, N., Holly, G., & Martin-Ortega, O. (2024). The EU Directive on Corporate Sustainability Due Diligence (CSDDD): The Final Political Compromise. *Business and Human Rights Journal*.

Chapagain, A., Hoekstra, A., Savenije, H., & 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. *Ecological Economics, 60*(1), 186-203.

Chen, F., Shen, Y., Liu, S., Yang, Y., & Wang, L. (2021). WATER FOOTPRINT OF TEXTILE INDUSTRY: A CASE STUDY OF CHINA. *Environmental Engineering and Management Journal, 20*(2), 237-245.

Claudio, L. (2007). Waste Couture: Environmental Impact of the Clothing Industry. *Environmental Health Perspectives, 115*(9), A449-A454.

Competition and Markets Authority - Government of the United Kingdom. (2024). *ASOS, Boohoo and Asda: greenwashing investigation*. Retrieved July 18, 2024, from https://www.gov.uk/cma-cases/asos-boohoo-and-asda-greenwashing-investigation

Darnall, N. (2006). Why Firms Mandate ISO 14001 Certification. *Business & Society, 45*(3), 354-381.

Delmas, M. A., & Burbano, V. C. (2011). The Drivers of Greenwashing. *California Management Review , 54*(1), 64-87.

Directorate-General for Economic and Financial Affairs. (2023). *In-Depth Review 2023: Italy.* European Commission.

ECHA. (2023). *Microplastics*. Retrieved July 16, 2024, from https://echa.europa.eu/hot-topics/microplastics

Ellerman, A. D., Convery, F. J., & Perthuis, C. d. (2010). *Pricing Carbon: The European Union Emissions Trading Scheme.* Cambridge: Cambridge University Press.

European Apparel and Textile Confederation. (2022). *EURATEX ReHubs TES Study.*

European Apparel and Textile Confederation. (2024). *Facts and Key Figures 2024 Of The Eeuropean Textile and Clothing Industry.* Brussels: EURATEX, Economic and Statistics.

European Comission. (2013). 2013/179/EU : COMMISSION RECOMMENDATION of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations. *Official Journal of the European Union*.

European Commission. (2008). DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 November 2008 on waste and repealing certain Directives. *Official Journal of the European Union*.

European Commission. (2022). DIRECTIVE (EU) 2022/2464 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL . *Official Journal of the European Union*.

European Commission. (2023). Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive 2008/98/EC on waste. Brussels.

European Environment Agency. (2019). Textiles in Europe's circular economy.

European Environment Agency. (2022). *Textiles and the environment: the role of design in Europe□s circular economy.*

European Parliament; Euorpean Council. (2024, February 28). DIRECTIVE (EU) 2024/825 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL. *Official Journal of the European Union*.

Fabietti, E. G. (2013). What Is Sustainability? A Review of the Concept and Its Applications. *Integrated reporting: Concepts and cases that redefine corporate accountability*, 21-40.

Federal Trade Commission-US Government. (n.d.). *Green Guides*. Retrieved July 17, 2024, from https://www.ftc.gov/news-events/topics/truth-advertising/green-guides

Finkbeiner, M. (2009). Carbon footprinting—opportunities and threats. *International Journal of Life Cycle Assessment, 14*, 91-94.

Finnveden, G., & Moberg, Å. (2005). Environmental systems analysis tools – an overview. *Journal of Cleaner Production, 13*(12), 1165-1173.

Fuse, M. (2012). Material Flow Analysis for Sustainable Resource Management. *Design for Innovative Value Towards a Sustainable Society: Proceedings of EcoDesign 2011: 7th International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, 517-518.

Gabrielli, V., Baghi, I., & Codeluppi, V. (2013). Consumption practices of fast fashion products: A consumer-based approach. *Journal of Fashion Marketing and Management: An International Journal, 17*(2), 206-224.

Gautam, K. K., & Tyagi, V. K. (2006). Microbial surfactants: a review. *Journal of Oleo Science, 55*(4), 155-166.

Giesen, C. v., Cucurachi, S., Guinée, J., Kramer, G. J., & Tukker, A. (2020). A critical view on the current application of LCA for new technologies and recommendations for improved practice. *Journal of Cleaner Production, 259*.

GITNUX. (2024). *GITNUX Marketdata Report.*

Gordon, J. F., & Hill, C. (2015). *Sustainable fashion : past, present, and future.* Bloomsbury.

Graedel, T. E. (2019). Material Flow Analysis from Origin to Evolution. *Environmental Science & Technology, 53*(21), 12188-12196.

Grothaus, J., Barrett, R., Liebenberg, K., Erb, M., Bauwens, K., Kernick, C., & Marlow, L. (2024). *Linklaters: The new EU Directive on Empowering Consumers for the Green Transition*. Retrieved July 18, 2024, from https://sustainablefutures.linklaters.com/post/102j2i9/the-new-eu-directive-on-empowering-consumers-for-the-green-transition

Guo, R., Tao, L., Li, C. B., & Wang, T. (2015). A Path Analysis of Greenwashing in a Trust Crisis Among Chinese Energy Companies: The Role of Brand Legitimacy and Brand Loyalty. *Journal of Business Ethics, 140*, 523-536.

Haes, H., Jolliet, O., Norris, G., & Saur, K. (2002). UNEP/SETAC life cycle initiative: background, aims and scope. *The International Journal of Life Cycle Assessment, 7*(4), 192-195.

Hauschild, M. Z., Goedkoop, M., Guinée, J., Heijungs, R., Huijbregts, M., Jolliet, O., . . . Pant, R. (2013). Identifying best existing practice for characterization modeling in life cycle impact assessment. *The International Journal of Life Cycle Assessment, 18*, 683-697.

Hellweg, S., & Canals, L. M. (2014). Emerging approaches, challenges and opportunities in life cycle assessment. *Science, 344*, 1109-1113.

Hur, E., & Cassidy, T. (2019). Perceptions and attitudes towards sustainable fashion design:. *International Journal of Fashion Design,, 12*(2), 208-217.

ICCA LCA Task Force. (2020). *How to Know If and When it's Time to Commission a Life Cycle Assessment.* International Council of Chemical Associations.

ICLG. (2024, 03 12). *Environment & Climate Change Laws and Regulations Italy 2024.* Retrieved from ICLG: https://iclg.com/practice-areas/environment-and-climate-change-laws-and-regulations/italy#

International Energy Agency. (2019).

International Working Group on GOTS. (2008). Global Organic Textile Standard Version 2.0.

ISO. (2006). ISO 14040: 2006. Environmental management—Life cycle assessment—Principles and framework. Geneva.

ISO. (2014). ISO/TS 14072:2014 Environmental management — Life cycle assessment — Requirements and guidelines for organizational life cycle assessment.

Italian Ministry of Environment and Energy Security. (2023, 08 28). *Promoting sustainability in Italy.* Retrieved from Ministero dell'Ambiente: https://www.mase.gov.it/pagina/promoting-sustainability-italy

Italian Ministry of the Environment and Energy Security. (2024). *National energy and climate plans.* Retrieved from European Commission: https://commission.europa.eu/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en

Jiang, R. J., & Bansal, P. (2003). Seeing the Need for ISO 14001. *Journal of Management Studies , 40*(4).

Kant, R. (2012). Textile dyeing industry an environmental hazard. *Natural Science, 4*(1).

Koroneos, C., Achillas, C., Moussiopoulos, N., & Nanaki, E. (2013). Life cycle thinking in the use of natural resources. *Open Environmental Sciences, 7*(1), 1-6.

Lee, E. J., Bae, J., & Kim, K. H. (2020). The effect of sustainable certification reputation on consumer behavior in the fashion industry: Focusing on the mechanism of congruence. *Journal of Global Fashion Marketing, 11*(2), 137-153.

Li, Z., Zhou, Y., Zhao, M., Guan, D., & Yang, Z. (2024). The carbon footprint of fast fashion consumption and mitigation strategies-a case study of jeans. *Science of The Total Environment, 924*.

Lin, H.-J., & Ma, H.-w. (2023). Analysis of green certification standards related to recycled materials involving textiles based on life cycle thinking. *Sustainable Production and Consumption, 41*, 107-120.

Marcketti, S. B., & Karpova, E. E. (2020). *The Dangers of Fashion Towards Ethical and Sustainable Solutions.* Bloomsbury.

Martínez-Blanco, J., Finkbeiner, M., & Inaba, A. (2015). Guidance on Organizational Life Cycle Assessment. UNEP; SETAC;.

Martínez-Blanco, J., Inaba, A., Quiros, A., Valdivia, S., Milà-i-Canals, L., & Finkbeiner, M. (2015). Organizational LCA: the new member of the LCA family—introducing the UNEP/SETAC Life Cycle Initiative guidance document. *The International Journal of Life Cycle Assessment, 20*, 1045-1047.

McKinsey & Company. (2023). *The State of Fashion 2024: Finding pockets of growth as uncertainty reigns.*

Meckling, J., & Allan, B. B. (2020). The evolution of ideas in global climate policy. *Nature Climate Change, 10*, 434-438.

Meijer, E. (2021, July 28). *Making LCA results count.* Retrieved from PRé Sustainability B.V.: https://pre-sustainability.com/articles/consider-your-audience-when-doing-lca/

Monseau, S., Sorsa, K., & Salokangas, H. (2024). CLEANER CLOTHES: THE EU TEXTILE STRATEGY AND SUSTAINABILITY IN THE TEXTILE SUPPLY CHAIN. *GEORGIA JOURNAL OF INTERNATIONAL AND COMPARATIVE LAW, 52*(2), 409-461.

Morgan, R. (2012). Environmental impact assessment: The state of the art. *Impact Assessment and Project Appraisal, 30*, 1-10.

Moutik, B., Summerscales, J., Graham-Jones, J., & Pemberton, R. (2023). Life Cycle Assessment Research Trends and Implications: A Bibliometric Analysis. *Sustainability, 15*(18).

Muthu, S. S. (2015). *Roadmap to Sustainable Textiles and ClothingRegulatory Aspects and Sustainability Standards of Textiles and the Clothing Supply Chain.* Springer.

Niinimäki, K., Peters, G., Dahlbo, H., Perry, P., Rissanen, T., & Gwilt, A. (2020). The environmental price of fast fashion. *Nature Reviews: Earth and Environment, 1*(189-200).

Noia, A. E., & Nicoletti, G. M. (2016). ISO 14001 CERTIFICATION: BENEFITS, COSTS AND EXPECTATIONS FOR ORGANIZATION. *STUDIA OECONOMICA POSNANIENSIA , 4*(10).

Norgate, T. E., & Rankin, W. J. (2000). Life cycle assessment of copper and nickel production. *Proceedings of MINPREX (2000)*, (pp. 133-138).

OEKO-TEX. (n.d.). *OEKO-TEX® STANDARD 100*. Retrieved July 15, 2024, from https://www.oeko-tex.com/en/our-standards/oeko-tex-standard-100

Oelze, N., Gruchmann, T., & Brandenburg, M. (2020). Motivating Factors for Implementing Apparel. *Sustainability , 12*.

Padeyanda, Y., Jang, Y.-C., Ko, Y., & Yi, S. (2016). Evaluation of environmental impacts of food waste management by material flow analysis (MFA) and life cycle assessment (LCA). *Journal of Material Cycles and Waste Management, 18*, 493-508.

Peng, S., Liu, J., & Geng, Y. (2022). Assessing strategies for reducing the carbon footprint of textile products in China under the shared socioeconomic pathways framework. *Climate Change Economics, 3*(1), 2240004.

Ponte, C. D., Liscio, M. C., & Sospiro, P. (2023). State of the art on the Nexus between sustainability, fashion industry and sustainable business model. *Sustainable Chemistry and Pharmacy, 32*.

Ponte, C. D., Liscio, M. C., & Sospiro, P. (2023). State of the art on the Nexus between sustainability, fashion industry and sustainable business model. *Sustainable Chemistry and Pharmacy, 32*.

Press Room - European Parliament. (2024). Products made with forced labour to be banned from EU single market.

Ramachandran, N. (2000). *Monitoring Sustainability: Indices and Techniques of Analysis.* New Delhi: Concept Publishing Company.

Remy, N., Speelman, E., & Swartz, S. (2016). Style that's sustainable: A new fast-fashion formula. McKinsey Global Institute.

Roos, S., Zamani, B., Sandin, G., Peters, G. M., & Svanström, M. (2016). A life cycle assessment (LCA)-based approach to guiding an industry sector towards sustainability: the case of the Swedish apparel sector. *Journal of Cleaner Production, 133*, 691-700.

Rossi, M., Papetti, A., Marconi, M., & Germani, M. (2021). Life cycle assessment of a leather shoe supply chain. *International Journal of Sustainable Engineering, 14*(4), 686–703.

Šajn, N. (2019). Environmental impact of the textile: What consumers need to know. European Parliamentary Research Service.

Sala, S., Amadei, A. M., Beylot, A., & Ardente, F. (2021). The evolution of life cycle assessment in European policies over three decades. *The International Journal of Life Cycle Assessment, 26*, 2295-2314.

Salman, M., Long, X., Wang, G., & Zha, D. (2022). Paris climate agreement and global environmental efficiency: New evidence from fuzzy regression discontinuity design. *Energy Policy, 168*(113128).

Sarkis, J., & Zhu, Q. (2017). Environmental sustainability and production:. *International Journal of Production Research, 56*(1-2), 743-759.

Shen, L., Worrell, E., & Patel, a. M. (2010). Present and future development in plastics from biomass. *Biofuels, Bioproducts and Biorefining: Innovation for a sustainable economy, 4*(1), 25-40.

Shirvanimoghaddam, K., Motamed, B., Ramakrishna, S., & Naebe, M. (2020). Death by waste: Fashion and textile circular economy case. *Science of the Total Environment*.

Solomon, J., & Rhianon Pel Edgley, C. (2008). The abandoned mandatory OFR: a lost opportunity for SER? *Social Responsibility Journal, 4*(3), 324-348.

Sull, D., & Turconi, S. (2008). Fast fashion lessons. *Business Strategy Review, 19*(2).

Sulzbacher, K., Balling, P., & Schembecker, G. (2013). INOSIM Bio - new approaches for bioprocess simulation and optimization. *Computer Aided Chemical Engineering, 32*, 865-870.

Szpilko, D., & Ejdys, J. (2022). European Green Deal-Research Directions: A Systematic Literature Review. *EKONOMIA I ŚRODOWISKO, 2*(81).

TerraChoice Environmental Marketing; . (2009). *The seven sins of greenwashing.*

Toxopeus, M., Koeijer, B. d., & Meij, A. (2015). Cradle to Cradle: Effective Vision vs. Efficient Practice? *Procedia CIRP, 29*, 384-389.

Tyteca, D. (1996). On the Measurement of the Environmental Performance of Firms: A Literature Review and a Productive Efficiency Perspective. *Journal of Environmental Management , 46*, 281-308.

UNEP. (2023). *Keeping the promise: Annual Report 2023.* United Nations Environment Programme.

UNEP/SETAC Life Cycle Initiative. (2016). *Global Guidance for Life Cycle Impact Assessment Indicators.*

United Nations. (2015). Transforming our world: the 2030 Agenda for Sustainable Development.

United Nations. (2023). *The Sustainable Development Goals Report 2023: Special edition.*

United Nations Environment Programme. (2011). *Division of Early Warning, and Assessment. UNEP year book 2011: emerging issues in our global environment.* UNEP/Earthprint.

United Nations Framework Convention on Climate Change. (2021). *Fashion Industry Charter for Climate Action*. Retrieved from United Nations Climate Change: https://unfccc.int/climate-action/sectoral-engagement-for-climate-action/fashion-charter#The-Charter

Verschoor, A. H., & Reijnders, L. (2001). The environmental monitoring of large international companies. How and what is monitored and why. *Journal of Cleaner Production, 9*(1), 43-55.

Vinci, G., D'Ascenzo, F., Ruggeri, M., & Zaki, M. G. (2024). A New Approach to Improve Sustainability: The Role of Organizational Life Cycle Assessment (O-LCA). *Innovation, Quality and Sustainability for a Resilient Circular Economy.*

Wang, Y. (2010). Fiber and Textile Waste Utilization. *Waste and Biomass Valorization, 1*(1), 135-143.

Woensel, L. V., & Lipp, S. S. (2020). European Parliamentary Research Service.

Wood, C. (2009). Comparative Evaluation of Environmental Impact Assessment Systems. In J. Petts (Ed.), *Handbook of Environmental Impact Assessment, Volume 2: Impact and Limitations* (Vol. 2, pp. 10-13). Birmingham: Blackwell Science.

Wrisberg, N., Haes, H. A., Triebswetter, U., Eder, P., & Clift, R. (2002). *Analytical tools for environmental design and management in a systems perspective: the combined use of analytical tools.* Kluwer Academic Publishers.

YANG, Z., NGUYEN, T. T., NGUYEN, H. N., NGUYEN, T. T., & CAO, T. T. (2020). GREENWASHING BEHAVIOURS: CAUSES, TAXONOMY AND CONSEQUENCES BASED ON A SYSTEMATIC LITERATURE REVIEW. *Journal of Business Economics and Management, 21*(5), 1486-1507.

Zhang, Z., Huang, J., Yao, Y., Peters, G., Macdonald, B., Rosa, A. D., . . . Scherer, L. (2023). Environmental impacts of cotton and opportunities for improvement. *Nature Reviews Earth & Environment, 4*, 703-715.