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Review

Life Cycle Assessment and Carbon Impact Assessment

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Abstract: The textile industry is actively investigating methods and technologies to enhance its environmental performance because of its substantial and well-known impact on greenhouse gas emissions worldwide. The internationally acknowledged Life Cycle Assessment (LCA) technique is a primary tool for calculating environmental consequences. Specifically for the computation of the impact of textile products in the apparel and footwear category, Product Environmental Footprint Category Rules (PEFCRs) are developed. A growing number of companies are joining the sustainable movement as customers become more conscious of the effects that the items they use have on the environment. These companies must examine their supply chains and product designs and search for ways to reduce pollution and carbon emissions to lower their effect. This paper has reviewed Case studies on the Life Cycle Assessment of T-shirts, the most commonly used garment.

***Keywords*:** acidification, carbon sink, eutrophication, ecotoxicity, nitrification

1. Introduction

The textile industry is the fifth-largest source of greenhouse gas emissions globally [1]. The textile processing sector generates around 1.2 billion tons of carbon emissions annually [2]. Fast fashion has been expanding quickly due to the growing global population, rising affluence, and purchasing power in developing countries. Fast fashion as a business model offers consumers frequent novelty of trend-led and low-priced products [3]. This has added to the textile industry's primary environmental challenges associated with water, water pollution, emissions of greenhouse gases (GHG), and waste management. Plenty of water, energy, and chemicals, such as insecticides and fertilizers for the growth of natural fibres crops (such as cotton and flax), are needed to manufacture textile fibres [4].

The primary sources of water contamination are the dyeing and finishing procedures for textiles, although microplastics released from synthetic fibres during use also contribute to the problem [1]. According to multiple studies, most of the growing textile waste is in landfills, making it a global problem. Due to increased garbage output from this consumption, landfills will be under pressure. Climate change is one of the biggest concerns regulated organizations have to deal with nowadays [5]. In this study, we selected T-shirt as a widely used knitted apparel wear manufactured using various machines and processing steps. The reviewed literature also pointed towards the study of T-shirts for comparative life cycle assessment.

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2. Carbon impact assessment

Carbon emissions are associated with the impact of carbon footprint on the environment. The term for carbon footprint stands for a number of gaseous emissions relevant to climate change associated with human production and consumption activities. Carbon impact assessment often varies regarding boundaries, scope, units of greenhouse gas emissions, and methodologies. Carbon emissions are divided into three categories.

- Scope 1 encompasses direct emissions from a sector, such as combustion emissions from natural gas and petroleum. This perspective is similar to the producer perspective used for emissions inventories of countries, states, etc.
- Scope 2 concerns the indirect emissions from electricity and steam purchases for a sector.
- Scope 3 involves indirect emissions from the entire supply chain until the production gate, also called cradle-to-gate or cradle-to-cradle emissions [6].

3. Life cycle assessment (LCA)

A life cycle assessment (LCA) is a scientific technique determining how a product or service will affect the environment. Life Cycle Assessment (LCA) offers comprehensive, scientifically based environmental information that helps us make sustainable business, political, and personal decisions [6]. by producing precise environmental data on goods and supply chains through an LCA, they ensured their sustainability claims were unquestionable [7]. The two categories of carbon activities related to the manufacture of textile products include:

- Carbon sink or carbon storage activities and
- Carbon sources or carbon emission activities.

Carbon storage plays a vital role (by fibrous plants) in the global carbon cycle. Biogenic Carbon was taken and stored in the plants and soil from the atmosphere during the growth of plant fibres; the radiative forcing is avoided, positively impacting climate change [8]. The reuse GHG emission reductions were more significant than recycling (reprocessing into wipers or reclaimed fibre felt and chemical recycling). This is because when reusing, GHG emissions from producing virgin raw materials can be avoided. GHG emissions from producing virgin raw materials cannot be avoided when recycling. The GHG from the incineration of post-consumer clothing can be avoided compared to the non-recycling case. The reduction in GHG from thermal recycling was the lowest of the recycling methods considered in this study. Therefore, used clothing must be reused and recycled, with incineration as a last resort [9]. Due to its complex fabric structure and high weight, Fleece jacket production produced greater carbon dioxide emissions. T-shirts gave the lowest amounts of tested fabrics [10]. This review paper aims to get an overview of the life cycle and carbon impact assessment of goals, boundaries, calculation tools and methodologies, standards, and frameworks for emission reporting.

4. Background of life cycle assessment

LCA made its appearance in the 1960s. Initially called Resource and Environmental Profile Analysis (REPA) or Eco-balance, the focus was on the packaging, and from the beginning, the effort was industry-led. In 1969, for example, Coca-Cola commissioned, for internal purposes, a study to compare aluminium, plastic, and glass bottles. However, with the development of environmental policies in the 1970s, governments soon became involved. In 1974, the Environmental Protection Agency (EPA) commissioned the first public and peer-reviewed LCA study on beverage container alternatives to inform American regulation. The EPA concluded that it was impracticable because too many products would need to be assessed, implying far-reaching micromanaging of private businesses [11].

Beyond governments and experts, the industry also developed links with international organizations. In the late 1990s, The Society of Environmental Toxicology and Chemistry (SETAC) established a partnership with the United Nations

Environment Programme (UNEP). Launched in 2002, the UNEP/SETAC Life Cycle Initiative (LCI) seeks to promote LCA globally, contributing to capacity building and helping to make LCA data more accessible and consistent [12]. Hosted by UNEP, the Initiative is a partnership of institutional members from government, business, science, and civil society. In its strategic approach for 2022–2027, the Initiative focuses on high-impact inter-governmental or sector-specific processes for sustainable development [13].

5. Objectives of life cycle assessment

- **Foundation for Sustainability Strategy:** LCAs comprehensively understand the environmental impact throughout the product life cycle to aid in strategic decision-making for sustainability improvements.
- **Purposeful Innovation:** LCA findings guide innovation by identifying areas with the highest potential for positive environmental impact and fostering collaboration with suppliers for sustainable product development.
- **Supporting Sustainability Claims:** LCAs offer reliable data to substantiate sustainability claims, enhancing credibility and trustworthiness with stakeholders and customers, particularly in an era of increasing scrutiny on greenwashing.
- **Competitive Edge and Brand Value:** Conducting LCAs demonstrates authenticity and transparency, distinguishing a brand as trustworthy and credible, elevating its competitive position, and enhancing brand value.
- **Strengthening Partnerships:** Engaging suppliers in LCA studies fosters collaboration, improves communication, and enhances supply chain transparency, strengthening partnerships and sustainability efforts.
- **Deepening Customer Relationships:** LCAs provide science-based evidence for sustainability achievements, enabling businesses to educate customers and stakeholders, build trust, and demonstrate the environmental benefits of their products, thereby fostering more profound relationships [14].

6. Methodology for life cycle assessment

- The carbon footprint is an analysis method limited to quantifying the direct and indirect greenhouse gas emissions (carbon dioxide, methane, etc.) associated with an activity, organization, or product as per ISO 14064. Part 1 contains the guidelines and specifications for quantifying greenhouse gas emissions, removals and reporting. Part 2 has the specification with guidance for quantification, monitoring, and reporting reductions in greenhouse gas emissions or removal of enhancements at the project level. Part 3 includes guidance and specifications for verifying and validating greenhouse gas statements [15].
- LCA techniques and standards have improved over the past 40 years. Internationally accepted LCA standards and recommendations have been developed mainly because of organizations and initiatives like the United Nations Environment Programme (UNEP) and the International Organization for Standardization (ISO). A general principle and framework for carrying out and reporting Life Cycle Assessments (LCA) studies is provided by ISO 14040 [16].
- The requirements and guidelines provided by ISO 14044 [17], two international standards created by the ISO. They apply to the textile industry as well as to other industries.
- ISO 14067: The carbon footprint of products, a crucial aspect in today's environmental discourse, is the central focus of this standard. It provides meticulous specifications and recommendations for measuring and disseminating a product's carbon footprint [18]. Sub-standards have been established in complement to these regulations, guidelines, and definitions for environmental claims. These include ecolabels for products and services designed to prevent false, misunderstood, or misleading claims, aiming to combat greenwashing.ISO14024–defines the environmental criteria for a group of products (Ecological labels of Type I, for example, Ecolabel).

- ISO14021–assessing Environmental labels Type II, known as Environmental self-declaration.
- ISO 14025 is a Type III Ecological label. It is the primary tool for obtaining an Environmental Declaration of Product (EPD).
- PAS 2050:2008-Specifications for assessing greenhouse gas emissions in the goods and services life cycle [19]. The Product Environmental Footprint (PEF), created by the European Commission, is a multi-criteria indicator of a product's environmental performance through its life cycle. It uses sixteen distinct impact categories, some of which include ozone depletion, resource depletion, and climate change [20].

As the importance of Life Cycle Assessment (LCA) grows, the number of available software tools for conducting these assessments is also increasing. The choice of software significantly influences the outcome and efficiency of projects [21]. Among all the three leading LCA software are:

- **Simapro** (developed by PRé Sustainability in the Netherlands).
- **Gabi** (developed by Sphera in the USA).
- **OpenLCA** (developed by Greendelta in Germany).

7. Stages of life cycle assessment

The five stages of Life Cycle Assessment correspond to the main steps in the product life cycle, which consist of 1. Raw Material Extraction; 2. Manufacturing and Processing, 3. Transportation and Distribution; 4. Usage and Retail, and 5. Waste Disposal and Recycling [22].

8. Approaches to life cycle analysis

There are several approaches to follow when carrying out the LCA. The three prominent approaches used for LCA analysis are enlisted as follows:

The cradle-to-gate approach stage measures the impact of removing raw materials at the manufacturer's gate. It is one of the simplest and least expensive methods.

The Cradle-to-grave approach measures the impact of raw material extraction on the end-of-life of the product. It is more comprehensive than the cradle-to-gate approach. It includes the phase when the product is in use, maintenance, and disposal.

The Cradle-to-cradle approach measures the impact of extraction of raw materials when the product is recycled or reused and starts a new life cycle. It is considered the most comprehensive assessment compared to other stages of the life cycle of the product. This approach promotes circularity, recyclability, and reuse. This means that the entire environmental impact of the product is assessed [23].

9. Phases of the life cycle assessment

According to the ISO 14040 and ISO standards, a life cycle assessment is a study with a systematic, phased approach with four interconnected phases.

- Defining the Goal and scope.
- Analysis of the Inventory of the inputs and outputs in a system.
- Impact assessment of the inputs and outputs.

- Interpretation of results [24].

It may be easier to understand the implementation of LCA in some of the studies. The following case studies have been presented to help understand the assessment of these four phases. They have also been compared with impact stages of life cycle assessment.

10. Case studies assessing the environmental impacts in the textile sector

Life cycle assessment is essential because cotton T-shirts are commonly used. A T-shirt garment was selected using three different textile materials for review. They were selected, and life cycle impact was assessed. Although the end product is common, these three case studies were from different countries and had different selections of base materials for the T-shirt. They cover all impact categories of life cycle assessment.

Case Study 1. A Woollen Undershirt was analysed for its potential environmental impact on wearing. A Life Cycle Assessment of which was analysed. The European Commission has prepared the Product Environmental Footprint Category Rules (PEFCRs) standardized, and "Made Green in Italy" guidelines were developed to calculate Woollen Undershirt Potential environmental impacts. These guidelines indicate that the cradle-to-gate boundaries and the data collected used the Ecoinvent 3.7 software database. The EF 3.0 method was used to conduct an impact assessment, which aligns with the Product Environmental Footprint (PEF) framework. To identify the primary sources of environmental impacts within the product life cycle, a contribution analysis developed is seen in Table 1.

Table 1. Potential impacts on the environment of a woollen undershirt

Impact category	Unit	Potential impact
Climate change	kg CO^2 eq	8.34×10^{-2}
Ozone depletion	kg CFC11 eq	2.21×10^{-9}
Ionizing radiation	kBq U-235 eq	1.58×10^{-3}
Photochemical ozone formation	kg NMVOC eq	8.93×10^{-5}
Particulate matter	disease inc.	1.19×10^{-8}
Human toxicity, non-cancer	CTUh	6.09×10^{-10}
Human toxicity, cancer	CTUh	2.75×10^{-11}
Acidification	mol H^+ eq	1.69×10^{-3}
Eutrophication, freshwater	kg P eq	2.00×10^{-5}
Eutrophication, marine	kg N eq	2.94×10^{-4}
Eutrophication, terrestrial	mol N eq	7.38×10^{-3}
Ecotoxicity, freshwater	CTUe	1.29
Land use	Pt	7.69
Water use	m^3 depriv.	1.82×10^{-2}
Resource use, fossils	MJ	2.58×10^{-1}
Resource use, minerals and metals	kg Sb eq	1.88×10^{-7}

It was found that the farming phase is the chief contributor to the total impact of all the impact categories the undershirt analysed. The grazing phase takes for 82% of the climate change indicator's overall impact. Throughout the value chain, the energy (electricity and heat) consumed was found to have impact values varying from 0.2% to 66.7%. The significant impact of energy for the indicators of ionizing radiation (66.7%) is mainly due to nuclear energy imported from France). As a climate change indicator, energy accounts for only 10% of the total impact. However, adopting sustainable practices, such as photovoltaic panels, by the company producing the undershirt has proved beneficial, demonstrating the potential for change and mitigation of environmental impacts. The chemical's impact from textile dyeing and processing resulted in a significant effect limited to human toxicity (cancer), which is not yet a robust LCA indicator. The transportation impact was lower than 3% of the overall impact categories of the analysed undershirt, indicating that it is a relatively minor contribution. Transport from Australia (where raw lanolin-containing wool is produced) to Italy Produce [25].

11. Case study 2. Life cycle assessment of cotton T-shirt in China

A 100% cotton T-shirt was evaluated for the potential environmental impacts using the cradle-to-grave approach. The environmental effects are evaluated using the GaBi version 6.0 software with built-in CML2001 and USEtox methodologies. Abiotic depletion (elements) burden is the primary contributor, especially in the dyeing stage (58.04%). The second contributor is the stage of upstream cotton cultivation (28.66%). The cotton cultivation stage primarily contributes to Eco toxicity potential, accounting for 82.9% of the total. Cotton cultivation contributes nearly 80% of T-shirts' life cycle water use, followed by the use and dyeing stages.

During the use stage (12.02%), dyeing stage (28.53%), cotton cultivation (16.71%), and making-up process (33.79%) cover the most acidification potential in the life cycle of the T-shirt. In the agricultural process, the Ammonia emissions contribute 12.5% to acidification. The wastewater emission with high loads of nitrogen, phosphorus, and chemical oxygen demand in washing activities consequently leads to the consumption stage being more responsible for the eutrophication potential. When hard coal is burned on-site to produce steam, the direct CO_2 emissions contribute to the dyeing process (34.79%). The dyeing process contributes 58.9% to the lifecycle is seen in Table 2.

The human toxicity potential—cancer (HTPC) burden of one T-shirt was assessed. Heavy metals, especially chromium, are discharged into freshwater when manufacturing Reactive dyes and pigments. Chromium has a carcinogenic effect on the human body and contributes 50.2% to the total HTPC[27].

Table 2. The LCIA results for one piece of T-shirt are based on CML 2001 and USEtox method

Impact category	LCIA method	Unit	Value
Abiotic depletion—elements (ADP-e)	CML	kg Sb-equiv.	9.74×10^{-6}
Abiotic depletion—fossil (ADP-f)	CML	MJ	58.1
Acidification (AP)	CML	kg SO^2-equiv.	0.0535
Eutrophication (EP)	CML	kg P-equiv.	0.0186
Global warming (GWP)	CML	kg CO_2-equiv.	6.05
Photochemical ozone creation (POCP)	CML	kg Ethene-equiv.	0.00316
Water use (WU)	-	kg	1770
Ecotoxicity (ECP)	USEtox	CTUeco	17.3
Human toxicity—cancer (HTPC)	USEtox	CTUh	3.08×10^{-7}
Human toxicity—non-cancer (HTPNC)	USEtox	CTUh	9.46×10^{-7}

12. Case study 3: Comparison of circularity strategies: Environmental sustainability assessment of a polyester T-shirt

Extracting virgin raw materials is the first step in the life cycle of a T-shirt. This study was conducted in China, and the data was gathered from a brand owner and a sub-contractor. The yarn was dyed and then knitted into fabric. The fabric was transported to the T-shirt manufacturing facility. The facility had cutting, sewing, printing, and finishing, followed by packing of the T-shirts. The T-shirt was transported for retail to Finland. The environmental sustainability assessment was done through the stages. The Figure 1 represents the scenario of a polyester T-shirt life cycle[28].

Various net life cycle impacts occur during the use phase. Of all impact categories, 46% (respiratory inorganics) and 74% (resource depletion, energy carriers) are the most significant contributors to environmental impact. The main reason is that the product undergoes resource-intensive washing and drying during the use phase.

Figure 2 represents the scenario of Characterized LCA results for scenario S1 with the EF 2.0 method and Contribution of life cycle stages. The second most important contributor, with a lesser impact, is during fabric production. The share of contribution is between 15% (eutrophication, marine) and 30% (water scarcity) of net impact. At the end of the life of T-shirts, incineration causes some emissions, which can be avoided. Some impacts generate only marginal benefits (net impact reduction between 1 and 3%). Lastly, transportation contributes a small fraction across all impact categories (net impact reduction between 0.1 and 3%)[28].

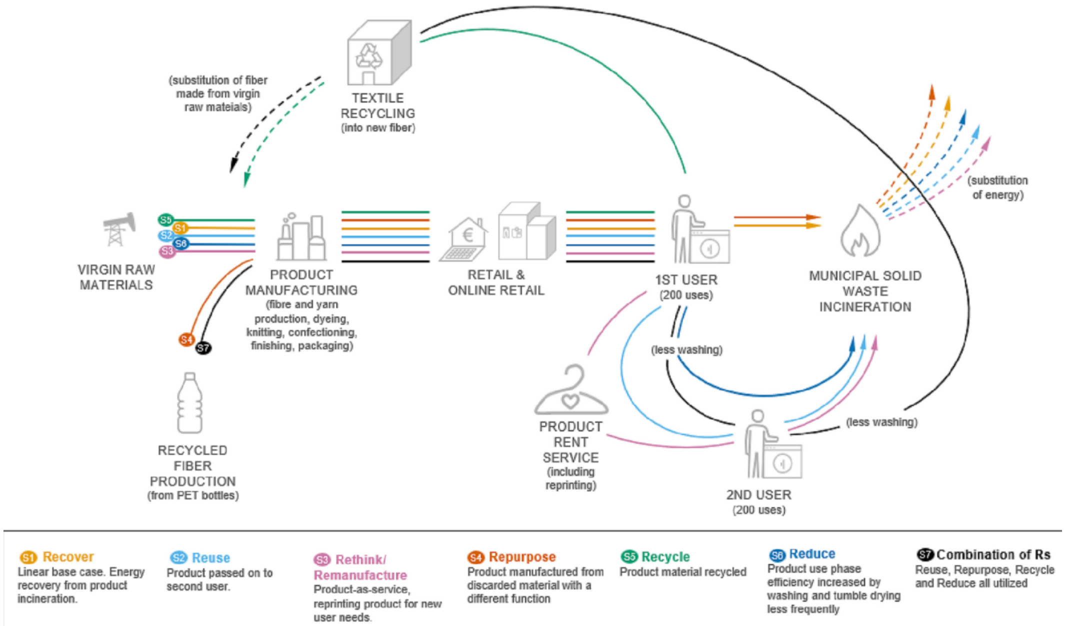

Figure 1. Scenarios of a polyester T-shirt life cycle

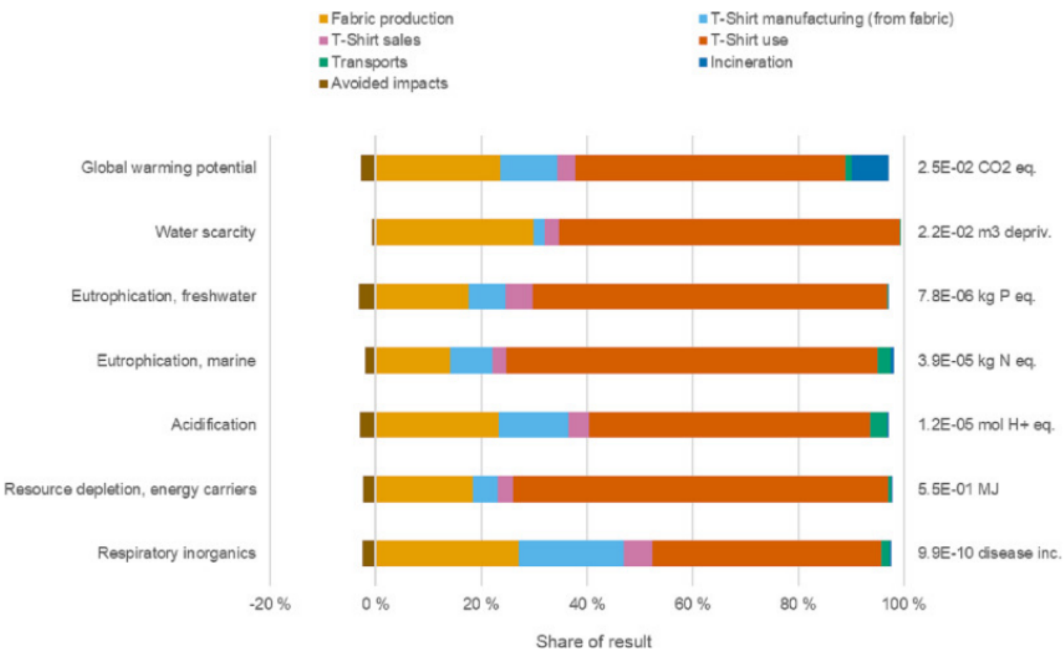

Figure 2. Characterized LCA results for scenario S1 with EF 2.0 method. Contribution of life cycle stages

13. Case study 4: Life cycle assessment of a cotton T-shirt

The Life Cycle Assessment (LCA), as an approach to evaluate the environmental effects of a 175-gram cotton t-shirt in the "cradle to grave" boundary, was used in this study[29].

The investigation revealed a single 175-gram cotton T-shirt with a carbon footprint of 8.46 kg-eq. The "global warming" column in Figure 1 illustrates how the usage phase accounts for 37.4% of the carbon dioxide equivalent greenhouse gas emissions, followed by the cultivation and ginning phase at 23.9%, wet processing at 18.4%, yarn production at 6.94%, apparel production at 12.3%, and supply at 0.59%. When waste is recycled and reused, a recovery of 12.1% is obtained at the end of the T-shirt's life. The percentage of recycling that has reduced greenhouse gas emissions by 12.1% is about 48%. The use and disposal stages are crucial regarding the environmental load is seen in Figure 3 [29].

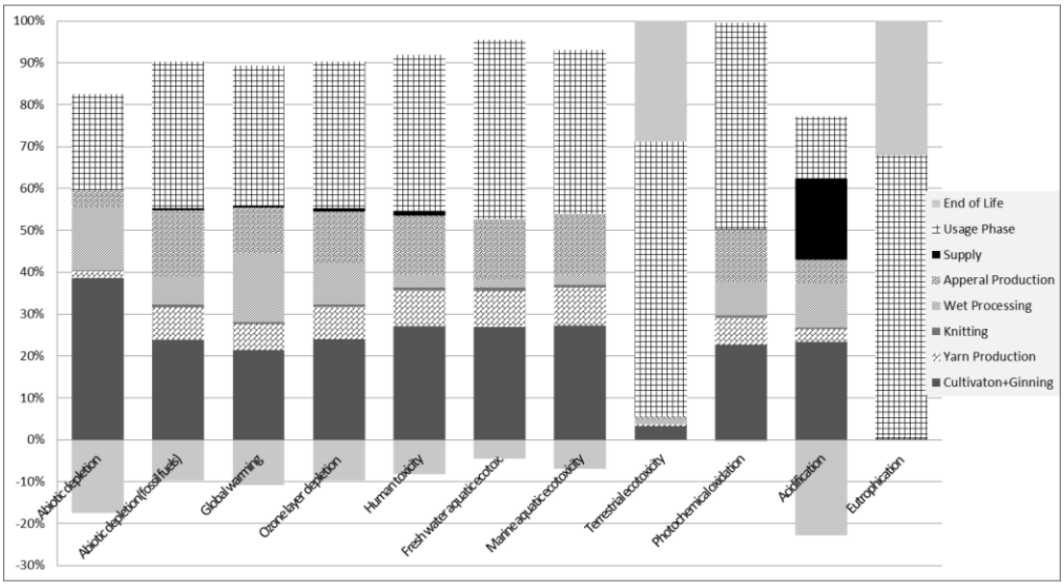

Figure 3. Characterization table of T-shirt

14. Case study 5: Carbon footprint of polyester T-shirt: A baseline scenario

Life cycle assessment, a rigorous and standardized technique to determine the potential environmental impact of any activity or product, is employed in this study using the specific standard ISO14040:2006. The baseline scenario for the carbon footprint of polyester T-shirts imported into Australia from China is established. This comprehensive study covers additional life cycle stages and most industrial manufacturing sub-processes is seen in Figure 4 [30].

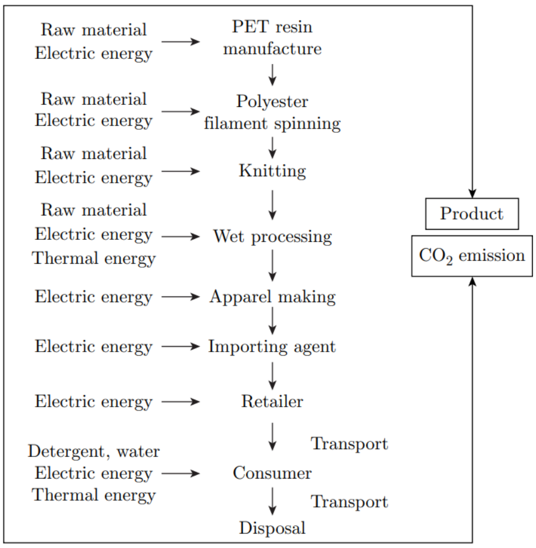

Figure 4. Boundary of life cycle assessment system

15. Case study 6: Lifecycle analysis (LCA) of a white cotton T-shirt and investigation of sustainability hot spots

The user determines when a textile product ends its useful life. There are four ways to dispose of fiber products: recycling, burning, landfilling, and reuse. By changing how they care for the clothing they purchase, consumers may drastically lower their carbon footprint at the point of sale. Cold water washing consumes less energy than warm or hot water washing. The washing machine heats the water with 80–90% of its energy[31].

In a proactive stance, the apparel industry has implemented measures to prevent accidents and health injuries related to work or the operation of employers' facilities. These efforts are aimed at ensuring a healthy working environment for all. Industry has also taken steps to mitigate the damaging effects of the workplace on the environment. A robust ventilation system further enhances the comfort of the working atmosphere. This comprehensive case study meticulously examined the social and environmental concerns that emerge during the production of white cotton T-shirts in Bangladesh, aiming to identify the footprints of the textile and RMG sectors is seen in Figure 5.

Social issues	Environmental Issues
• Employment • labor/management relations, OHS (Occupational health and safety) • Equal opportunity • Equal remuneration • Child labor • Freedom • of association • Security practices • Anti-corruption etc.	• Materials ❖ fertilizers ❖ pesticides ❖ fungicides ❖ auxiliaries ❖ raw materials ❖ packaging materials • Energy • Water • Biodiversity • Emissions • Effluent and waste • Transport • Supplier environmental assessment etc

Figure 5. Social and environmental issues involved in the lifecycle of T-shirt

16. Discussion

The examined effect categories determine how an LCA and a carbon footprint differ. One area of environmental effect that is the focus of a carbon footprint is greenhouse gas emissions (CO_2). In the interim, additional effect categories, such as ocean acidification, water use, and land use, can be included by an LCA. A product, activity, or process's whole life cycle assessment includes a carbon footprint analysis subcategory.

Based on the review of Case Studies 1–3, the impact on the life cycle assessment depends on the type of raw material, its process activities, and the end-of-life disposal. Polyester's potential global warming value is less than other manufacturing process activities.

Further, the scope for life impact of cotton T-shirts in India, from manufacturing to end-of-life disposal process, and data for this country's region help to evaluate the impact categories of life cycle inventories.

Further study on social life cycle assessment is required. This should include the impact on stakeholders, such as local communities, workers, and end consumers. The impact can be grouped into different categories measured by several indicators for workers' salary, working time, labour force, discrimination, health, and safety[32].

17. LCA and challenges in the textile industry

Based on the review of case studies 1 to 6 and challenges in the textile industry, as below that

- Life Cycle Assessment can be a challenging activity for the fashion industry. Several brands have faced critical problems in conducting the LCA. Some of the difficulties faced by many brands are summarised below:
- Cost and Expertise: Cost can be a major constraint while conducting the LCA. Brands will have to invest in the purchase of licenses for software and acquire extensive access to databases. Software like Gabi and Simapro are available. Ecoinvent is an example of a Database. These are costly. Apart from these, the brands will need experts and specialists help, as the process is complex and will consume time.
- Data Collection: The textile industry faces the challenge of conducting LCA. It is only possible by gathering accurate and comprehensive data. Transparency can be another challenge when Suppliers do not or cannot provide the necessary information. Suppliers need to be more forthcoming with the required information on their processes. Tracking impacts, specifically consumption of water and energy, release of chemicals, or generation of waste, can be difficult.
- Supply Chain Complexity: The supply chains of the Textile industry are complicated. There are many stages, several stakeholders, and different geographical locations. The Life Cycle Assessment for environmental impact will need inputs from each stage, starting with sourcing raw materials, production, transportation, and end-of-life of the product[34].
- An LCA may not be suitable in situations with spatially varied effects, sensitivity, social or economic dimensions, exceeding toxicity limits, significant changes involving nonlinear responses, or changes in other systems, such as consumer behavior or economic structure[33].

18. Limitations of the LCA approach

Life Cycle Assessment (LCA) is a method used to evaluate the environmental impacts of products or services throughout their life cycle. However, it has several limitations of the LCA approach, including insufficient data availability and quality, regional and temporal variations, complexity and scope, interpretation challenges, subjectivity and assumptions, exclusion of non-environmental factors, cumulative effects, time and resource intensiveness, and methodological differences.

Data availability and quality can be inconclusive due to the need for detailed, high-quality data for all stages of a product's life cycle. Regional and temporal variations can also affect the results. The definition of the system boundary can be subjective, leading to different conclusions. Result interpretation can be complex and difficult to interpret, especially when comparing different products or processes with different impact categories. Subjectivity and assumptions can also influence outcomes and expert judgment.

LCA is time and resource-intensive, especially for complex products or services with long life cycles. Methodological differences and software and tool limitations can also impact the accuracy of LCA results.

19. Conclusions

- The LCA study depends on the selected methodology and approach, such as cradle-to-cradle, cradle-to-grave, or cradle-to-gate. Before starting the assessment, one needs to know whether the impact factor, such as mid-term or long-term impact, is considered.
- Carbon emissions can be studied by sector, cluster, or country. The study's findings highlight the value of a multidirectional strategy, in which small-scale changes made at various stages of a product's life cycle enhance its overall sustainability.
- The LCA analysis assessed various production and consumption methods rather than validating any particular production plan. This was done to increase efficiency and understanding of the environmental effects of products and process activities.

- The textile and Fashion industry must overcome some complexities and hurdles in implementing environmental sustainability.

- To reduce the carbon footprint or product life cycle impacts, recommendations as below that selection of input materials like recycled water or reused textile materials and water, renewable energy sources, process optimization like during coloration reduced the steps for cold wash, hot wash, and cold temperature dyeing methods, wash less or limited-washed required products, wrinkle- or crease-free products to avoid ironing steps, monitoring of each and every step, and make an industry benchmark for the carbon footprint of each product.

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