LIFE CYCLE ENVIRONMENTAL IMPACT ASSESSMENT OF TEXTILES AND APPAREL

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Abstract

The significant environmental impacts of the production and consumption of textiles and apparel have attracted widespread attention. However, assessing the environmental impacts of textiles and apparel has been a challenge due to the diversity of product types and the complexity of life cycle chains. To this end, this paper discusses and summarises several key issues in the life cycle environmental impact assessment of textiles and apparel, including system boundaries, data collection and allocation, accounting methods, and impact assessment, based on a review of the research progress in product environmental footprint analysis within the textile field. It was found that existing publications are mostly based on “cradle-to-gate” and “gate-to-gate” boundaries, focusing on the impacts associated with the production processes, while ignoring the consumption phase. Data collection is generally conducted manually, which is costly and inefficient. Most assessments have focused on carbon and water footprints, with a few concerning chemical footprints. Some studies have proposed product environmental footprint accounting methods based on modularity, but these are still in the early development stage. The assessment results include three levels: product, organisation and region, but there is currently a lack of a unified standard system to enable valuable comparative assessments within the different levels. Given the life-cycle characteristics of textiles and apparel, we believe that the uncertainty of results caused by the heterogeneity of consumer behavior should be addressed before extending the system boundaries to the use stage, technologies such as blockchain are recommended to replace the traditional manual collection of activity data, and additional impact categories need to be considered, as well as their comprehensive assessment. Besides, more effort should be made to improve the modularity-based accounting methods and complete the modular database. A more detailed and standardised system is also needed for the calculation and assessment methodology of the environmental footprint of textiles and apparel, especially for the impact categories related to

chemical use. The conclusions drawn from this study will inform the future development of life cycle environmental impact assessment of textiles and apparel.

Introduction

Textiles and apparel, a necessity of life that is both practical and aesthetically pleasing, are in relatively high demand and consumption globally. It is estimated that global consumption has risen to an estimated 62 million tons per year and is expected to reach 102 million tons by 2030 (Global Fashion Agenda et al., 2019; Niinimaki et al., 2020). However, the industrial manufacture of textiles and apparel, such as the printing and dyeing stage, consumes a large amount of energy, fresh water and chemicals, resulting in the emission of massive greenhouse gases (GHGs), wastewater and pollutants, posing a serious threat to the ecological environment (Chen et al., 2017). Meanwhile, the use stage, which consumes a lot of electricity, water and detergents due to frequent use and laundering (including washing, drying and ironing) operations (Bao et al., 2017; Liu et al., 2019), has also been disclosed to have significant negative environmental impacts (Wiedemann et al., 2021), in some cases even exceeding those of the product manufacturing process, depending on the product type and impact category (Yasin et al., 2016).

An important prerequisite for efficient energy, water and pollution management in the textile sector is the accurate accounting and assessment of the environmental impact caused by energy and water consumption, wastewater and pollutant emissions from textiles and apparel. However, due to the complexity of the production chain, the diversity of the products involved, the wide variation in processing modes, and the extensive management of enterprises (Luo et al., 2021), it is quite difficult to solve the key issues of data allocation, quantitative calculation and comprehensive assessment when adopting the existing international generic technical specifications and standards for life cycle environmental impact assessment of textiles and apparel.

In recent years, many scholars and practitioners have devoted themselves to solving the above-mentioned difficulties and have made certain achievements. To this end, this paper reviews the research progress regarding the life cycle environmental impact assessment of textiles and apparel, with a focus on the analysis and discussion of issues in system boundaries, data collection and allocation, accounting methods, and impact assessment. On this basis, some suggestions are made for the future development of life cycle environmental impact assessment of textiles and apparel in the context of existing production and consumption patterns, aiming to provide feasible solutions for the sustainable development of the industry.

Life Cycle Environmental Impact Assessment of Textiles and Apparel

The life cycle of textiles and apparel includes a series of stages such as raw material extraction, industrial manufacturing, distribution and transportation, consumer use and end-of-life disposal, each of which has impacts on the ecology and human health due to the extensive use of energy and materials. It is typical to reduce negative environmental impacts by conducting quantitative assessments and thus identifying environmental hotspots and proposing optimized solutions. A review of previous publications reveals that the product environmental footprint method has played an important role in assessing the life cycle environmental impacts of textiles and apparel.

The 'footprint' is applied to describe the human occupation of natural resources and the burdens and impacts of human activities on the environment (Hoekstra, 2008; Society of Environmental Toxicology and Chemistry & United Nations Environment Programme, 2009). Since Rees (1992) first introduced the concept of "ecological footprint" in 1992, scholars worldwide have gradually discovered the importance of 'footprint' in the field of environmental assessment. A great number of footprint indicators such as water footprint, energy footprint (Ferng, 2002), chemical footprint, carbon footprint and waste footprint (Laurenti et al., 2017) have been proposed successively, which have greatly enriched the connotation and status of footprint, and environmental footprint has become one of the hot research topics in the field of sustainability quantification.

Among them, product carbon footprint (PCF) and product water footprint (PWF) were first applied to the textile field with a wealth of research accumulated. Additionally, other impact categories have received attention in recent years, especially a growing number of studies associated with product chemical footprint (PChF), as summarized in Table 1.

Footprint indicator	Product category	Reference
Product carbon footprint	Cotton T-shirt	Nagel (2010); Li et al. (2019)
	Wool sweater	Bevilacqua et al. (2011)
	Cotton shirt	Wang et al. (2015)
	Polyester flannel dyeing and printing fabric	Chen et al. (2016)
	Denim jeans	Karthik & Murugan (2017); Luo et al. (2022)
	Cellulose carbamate fibers from chemically recycled cotton	Paunonen et al. (2019)
	Cashmere fabrics	Chen et al. (2021)
	Recycled polyester textiles	Qian et al. (2021a)
Product water footprint	Jeans	Chico et al. (2013); Luo et al. (2022)
	Polyester flannel dyeing and printing fabric	Chen et al. (2016)

Footprint indicator	Product category	Reference
	Cellulose carbamate fibers from chemically recycled cotton	Paunonen et al. (2019)
	Silk apparel	Yang et al. (2020)
	Viscose textiles	Chen et al. (2020); Zhu et al. (2020); Qian et al. (2021c)
	Cashmere fabrics	Chen et al. (2021)
	Recycled polyester textiles	Qian et al. (2021a)
	Cotton fabrics	Li et al. (2021)
	Polyester fabric	Wang et al. (2022)
Product chemical footprint	Cotton T-shirt	Roos & Peters (2015)
	Denim jeans	Li et al. (2020); Luo & Li (2021)
	Cotton fabric	Qian et al. (2021b)
	Woolen textiles	Ji et al. (2021)
	Yarn dyed fabric	Guo et al. (2022b)
	Polyester fabric	Qian et al. (2022)

Table 1. Study on the life cycle environmental impact assessment of textiles and apparel

Discussion

When applying product environmental footprint methods to textiles and apparel, problems arise in defining system boundaries, collecting activity data, and accounting for and evaluating impacts due to the complexity of life cycles and the diversity of material types.

System boundaries

The system boundaries are the basis of product environmental footprint accounting, and the consistency of system boundaries is an important prerequisite to ensure the accuracy and comparability of results. The system boundaries can be divided into time boundary and space boundary, where the former refers to the time span between the starting point and the end point of the product life cycle; the latter refers to the input and output of various substances involved in the product time boundary, as shown in Figure 1.

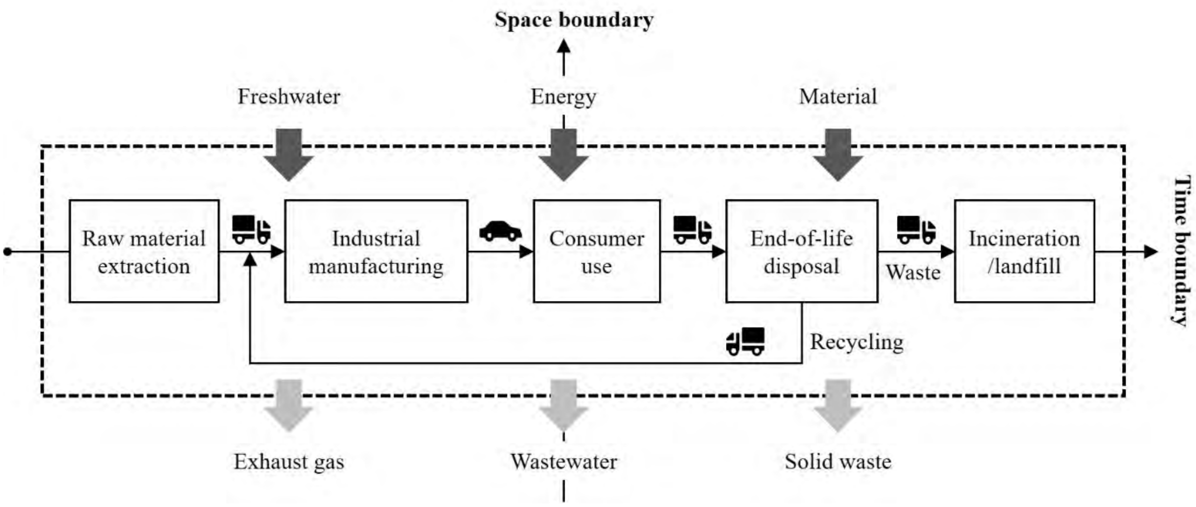

Figure 1. Typical system boundaries for textiles and apparel

When conducting an assessment, partial or full scope can be selected as the time boundary depending on the research objectives. It was found that studies with “cradle-to-gate” (that is, from raw material extraction to a process in the product supply chain) (Paunonen et al., 2019; Zhu et al., 2020; Chen et al., 2021; Qian et al., 2021a) and “gate-to-gate” (that is, from raw material processing to product output) (Chico et al., 2013; Chen et al., 2016; Chen et al., 2020; Yang et al., 2020), boundaries dominate the available publications, focusing on the environmental impacts associated with the industrial manufacturing of textiles and apparel.

In contrast, there are few studies on the full life cycle (that is, the “cradle-to-grave” scope) (Bevilacqua et al., 2011; Luo et al., 2022), especially the lack of a research perspective on consumer use (Huang et al., 2013; Laitala et al., 2018). The main reason for the exclusion of use stage is the significant uncertainties in the way textiles and apparel are used and cared for due to varied behavior patterns in terms of household activities such as dressing, laundering, and dry cleaning (Laitala et al., 2018).

While simplified life cycle assessment (LCA) models are allowed, some scholars have pointed out that the lack of full life-cycle considerations fails to provide complete support for informed decision making, as it is difficult to identify the most critical contributors to the overall environmental impact and is likely to lead to environmental burden shifting (Wiedemann et al., 2020; Luo et al., 2022). For example, reducing the wash cycle during fabric dyeing and finishing tends to cause product fading during use, resulting in water savings in production being offset or even outweighed by resource waste due to shorter product life.

Data collection and allocation

Primary activity data, including data from real-time metering, field tests and process flow cards, are considered to be more accurate than historical or empirical data. In fact, however, real-time measurements of energy consumption, water consumption, and wastewater discharge are not yet available for most textile producers, especially small and medium-sized enterprises, and with multiple products often being produced simultaneously in the same area, the activity data obtained from enterprises are therefore often aggregated rather than process-level data.

The ISO series of standards provides data allocation methods based on physical relationships and economic values between products to address the above issue (Cherubini et al., 2011; Rice et al., 2017). However, these methods mainly target the product and plant level without subdivision to the production process level. Considering the decentralized production and processing characteristics of textiles and apparel, the calculation results obtained by the two allocation methods are subject to large uncertainties and fail to achieve fine management. In this regard, Li et al. (2019) put forward a process-level allocation methodology, which helps to deduce the technical differences on various processes.

On the other hand, the complex process chain of textiles and apparel often poses a great challenge to the collection of activity data. The traditional and currently mainstream collection methods are manual means, which are costly, time-consuming and inefficient, often with poor data transparency and sharing. In this regard, some scholars have introduced blockchain technology into the life cycle environmental impact assessment of textiles and apparel (Agrawal et al., 2021; Carrieres et al., 2022). Multiple stakeholders in the value chain can thus share and automatically access relevant data and information at different stages, making the quantification, accounting and traceability of products more transparent and credible. However, limited by the acceptance and enthusiasm of enterprises, the accessibility and user-friendliness of the technology, as well as the mutual compatibility and scalability of the blockchain industrial ecology, more work remains to be done to make the technology practical.

Accounting methods

As mentioned earlier, PCF and PWF, as well as PChF, are hot topics in the field of environmental sustainability research for textiles and apparel.

<u>Product carbon footprint</u>

The PCF is used to quantify GHG emissions and GHG removals in a product system, which converts various GHGs into CO_2 equivalent with the help of global warming potential (GWP) to describe the impact of climate change. Currently, the PCF of energy and materials is estimated by multiplying GHG emission factors (that is, coefficient relating activity data with GHG emissions) with actual consumption, which is the most popular and recommended accounting method by IPCC (IPCC, 2006; 2019). Obtaining emission factors for energy and materials commonly used in the production and consumption of products is therefore one of the key fundamental tasks in assessing the environmental impacts of textiles and apparel in relation to global warming. Generally, emission factors obtained from the site, including direct measurements and mass balance, are considered to have the highest accuracy, followed by those obtained from the same process or equipment based on relevant experience and evidence, and those based on regional and national characteristics. In cases where none of the above is available, some international common factors are considered. At present, most of the energy emission factors have been published by relevant institutions (International Energy Agency, 2021; Chinese Academy of Environmental Planning et al., 2022; United States Environmental Protection Agency, 2022), and theoretical, methodological and empirical studies have been conducted (Li et al., 2014), but due to the differences in regional development levels, some small and medium-sized enterprises and less developed regions still have no access to the optimal emission factors. Moreover, the life cycle of textiles and apparel involves more complex types of materials than energy, and emission factors for many materials are still under research.

Product water footprint

The concept of PWF originated from “embedded water” and “virtual water” proposed by Hoekstra and Hung (2002). It was originally defined as the amount of water required for all goods and services consumed by a known amount of the population (individual, region, country or world) over a certain period of time, consisting of blue water (surface and groundwater), green water (rainwater that does not become runoff) and grey water (the volume of freshwater required to assimilate the pollutants based on existing ambient water quality standards) footprints. In 2014, ISO 14046 standard was released, which defines the PWF as an indicator to quantify the potential environmental impacts associated with water quantity and quality based on LCA theory, and divides it into water scarcity and water degradation footprints, the latter of which can be subdivided into water eutrophication, water acidification, water ecotoxicity and water alkalization footprints (Chen et al., 2020) according to pollutant categories.

After the concept of PWF was proposed and relevant standards were released, many researchers tried to analyse the water issues in the textile field (Chen et al., 2015; Wang et al., 2017a; Chen et al., 2019). However, it was found that in practice, the long production chain, the large geographical span and the different background concentrations of water quality properties in different regions led to an inaccurate reflection of actual phenomenon. It is therefore necessary to consider temporal and geographical variations when assessing the PWF of textiles and apparel. Ding et al. (2017) systematically analysed the water consumption and wastewater discharge characteristics during the product life cycle, and developed a PWF assessment model for textiles and apparel based on regional and seasonal water stress indexes.

On the other hand, existing PWF systems assess water quantity and quality in different ways, and fail to reflect the overall environmental load in terms of water resources, thus making it difficult to compare various products and processes. In this regard, the LCA polygon method was adopted by Zhu et al. (2020), Yang et al. (2020) and Qian et al. (2021c) to enable a comprehensive PWF assessment for textile products.

Product chemical footprint

The PChF, also known as product toxic footprint, is designed to quantify the potential toxic effects of products on the environment and human health caused by the use of chemicals and their emissions (Guttikunda et al., 2005; Hitchcock et al., 2012). It was Roos (2015) who first fully discussed the toxicity issues of textile chemicals in LCA studies. By accounting for the PChFs of two types of hospital garments, it was demonstrated that the toxicity potential of textile chemicals affects the environmental performance rankings of textiles (Roos et al., 2015). Furthermore, the toxic effects of textile chemicals were calculated using a quantitative model (that is, USEtox model) (Gandhi et al., 2011) and two semi-quantitative methods (that is, score system and strategy tool) (Laursen et al., 2002; Askham et al., 2012) with cotton T-shirts as an example. The USEtox model was found to be more realistic for environmental management among the three methods (Roos & Peters, 2015). Based on the studies of Roos and her colleagues, Li et al. (2020) calculated the PChFs in the production of jeans using the USEtox model, and analysed in more depth the toxic effects of textile chemicals, as well as issues related to chemical management. In the past two years, Ji et al. (2021), Guo et al. (2022a), Qian et al. (2021b) and Qian et al. (2022) worked on improving the PChF accounting and assessment methods.

Compared with PCF and PWF, however, the research base of PChF is still weak, with its evaluation model and methodological system to be unified. Although the PChF is of great practical significance for realising the effective management of toxic and hazardous chemicals in the textile field, the problems of complex chemical composition, multiple testing procedures and difficult data collection in the actual industrial production process have hindered its further development.

Modularity-based accounting method

The plethora of material varieties and life cycle processes involved not only increase the difficulty of obtaining primary data oriented to specific products and processes, but also further hinder the measurement of environmental impacts. In addition to the data collection aspect, some scholars have introduced modularity theory from the perspective of accounting methods, which decomposes complex production process into multiple environmental footprint units (that is, modules) to clarify the complex relationships among products, workshops, and processes, thus enabling the creation of unlimited product variants using a limited set of modules.

Wang (2015) incorporated modularity into the PCF assessment of textiles and apparel, dividing the industrial PCF into several process modules. By matching process and technical parameters, these modules can be reused directly or partially modified for reuse. Li et al. (2021) developed a novel process-level PWF assessment method for textile production based on modularity, clarifying in detail the decomposition and definition of PWF units, as well as calculation, coding, reuse and assembly issues. Luo et al. (2022) further extended the time boundary from the previous industrial manufacturing stage to the whole life cycle, considering both PCF and PWF.

Although the demonstration of existing studies confirms to some extent the superiority of the modular method over traditional methods in modeling, assessment, and analysis, as noted in the study by Luo et al. (2022), the method is highly dependent on the modular database. Therefore, the completion of the modular database will be the focus of future work.

The data collection of each module can also be accomplished through the integration of emerging technologies such as blockchain and the Internet of Things to reduce the huge workload of manual collection. Furthermore, a suite of software for computing and analysing modules could be developed to enable faster and more accurate assessments.

Impact assessment

The life cycle environmental impact assessment of textiles and apparel includes three levels: product, organization and region. At the product level, the modularity-based accounting methods are considered more favorable. On the one hand, through the reuse and assembly of different modules, the environmental footprint of different products and different production processes can be assessed and compared (Luo et al., 2022). On the other hand, by reusing and assembling similar modules, the environmental footprint of products from different producers and under different production conditions can be assessed and compared (Li et al., 2021).

The organisation-level assessments involve different dimensions such as enterprises and sectors. For enterprises, accounting for the product environmental footprint allows them to optimise the production processes and technologies, so as to enhance the competitiveness of enterprises in the same category (Ren et al., 2019), while sector-based assessments can promote the restructuring of energy and resource consumption, thus improving the overall environmental efficiency of the industry (Li et al., 2017; Wang et al., 2017b). In addition, since the assessment of enterprises is influenced by more factors, such as the planning and practices related to environmental management, the overall environmental performance of enterprises can be further evaluated by combining management indicators. Zhu et al. (2018) constructed a GHG management evaluation system applicable to textile enterprises based on industry characteristics and product attributes.

The regional level emphasizes the pressure that the production and consumption of a product puts on the resources and environment of the region where it is located. Different regions have different capacities to withstand environmental pressures (Pfister & Bayer, 2014); in other words, the environmental impact of consuming or discharging the same quality of material varies. For example, water resources are abundant in eastern China, while scarce in the west; therefore, high water consumption in the production of products has a greater impact on the western region. Moreover, population densities differ between regions (Steinberger et al., 2009), which is particularly important for human health. China and India, for instance, are much more densely populated than Europe or the United States, so the former two have lower natural resources and environmental capacity per capita than the latter two.

To make the results scientific and comparable, assessments between different products, organizations and regions need to be conducted under a standardised system. Although many standards have been published internationally to regulate the environmental footprint assessments, most of them are generic specifications applicable to all product categories, rather than specific ones. Given the complexity of the production and consumption of textiles and apparel, it is necessary to develop technical requirements based on the characteristics of such products. Currently, a research team led by Professor Ding from Donghua University in China has launched group and industry standards for accounting and assessment of PCF and PWF of textiles and apparel (China National Textile and Apparel Council, 2018; Ministry of Industry and Information Technology, 2021). Further internationalisation of standards is needed in the future. Besides, there is a lack of standardisation related to PChF.

Conclusions and Future Work

Although much effort has been put into solving the difficult-to-measure and difficult-to-assess problems facing the life cycle environmental impact assessment of textiles and apparel, what can be found is that there are still some issues that have yet to be explored and resolved. In order to effectively carry out the assessment and reduce the environmental impacts associated with the production and consumption of textiles and apparel, thus promoting the sustainable development of the industry, the following directions can be the focus of future work:

(1) The heterogeneity of consumer behavior leads to great uncertainty in environmental impacts during the use stage, which makes most studies exclude this stage from the time boundary, creating an incomplete assessment. Follow-up work should attempt to address this uncertainty in the use stage. Factors influencing different consumer use and care behaviors, and the influential mechanisms that shape such behavioral changes, deserve further investigation.

(2) In terms of data collection, manual means are commonly adopted currently, which is costly and inefficient. The data collection and transmission methods based on blockchain technology have received attention, and further exploration is needed to see whether the traditional manual collection can be completely replaced in the future.

(3) Despite the high priority given to the life cycle environmental impacts of textiles and apparel, existing studies have been mainly limited to climate change, water depletion and pollutant emissions associated with chemical use. Some other impact categories, such as waste emissions, especially environmental issues related to microplastics, have not been adequately studied. Meanwhile, achieving a comprehensive assessment of all types of impact categories would reflect the overall environmental load of products and facilitate effective comparisons between products.

(4) Regarding the accounting method, although the modularity-based product environmental footprint method has proven to be superior to traditional methods in modeling, assessment and analysis, the method is highly dependent on the modular database and therefore requires continuous efforts in database construction.

(5) More work needs to be done on standardisation of life cycle environmental impact assessments and development of technical requirements for textiles and apparel, in order to standardise models for accounting and assessing the environmental footprints of products, particularly with respect to quantification of chemical use.

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