REVIEW OF GREENHOUSE GAS EMISSIONS MODELLING FOR TEXTILE END-OF-LIFE MANAGEMENT SCENARIOS

UBC SUSTAINABILITY SCHOLARS REPORT

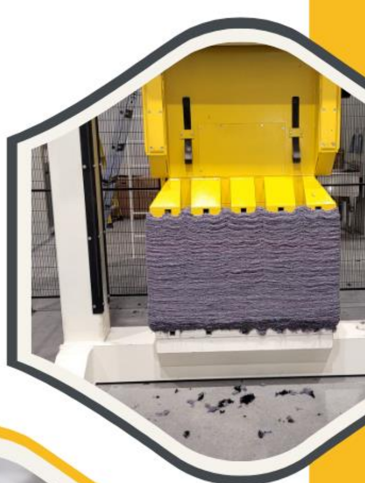
Prepared by: Katherine Le, UBC Sustainability Scholar, 2023

Prepared for:
Textile Lab for Circularity
Tracy Lydiatt, Managing Director
Emily McGill, Research & Collaboration Coordinator

Leverage Lab
Sara Blenkhorn, Collaborative Innovation Partner

March 2023






This report was produced as part of the UBC Sustainability Scholars Program, a partnership between the University of British Columbia and various local governments and organizations in support of providing graduate students with opportunities to do applied research on projects that advance sustainability across the region.

This project was conducted under the mentorship of the Textile Lab for Circularity (TLC) staff. The opinions and recommendations in this report and any errors are those of the author and do not necessarily reflect the views of the Textile Lab for Circularity or the University of British Columbia.

Acknowledgements

The author would like to thank the following individuals for their contribution, feedback, and support throughout this project:

Tracy Lydiatt and Emily McGill from the Textile Lab for Circularity (TLC), for their mentorship, each providing their unique insights and skillsets, guidance, and feedback throughout this project.

The TLC project team: Sara Blenkhorn, Megan Bourassa, Jennifer Henry

Karen Taylor from UBC Sustainability, for her exemplary coordination of this program.

Participants of the TLC Textile End-of-Life GHG Emissions Roundtable discussion that took place on February 15, 2023.

The author acknowledges that the work for this project took place on the unceded ancestral lands of the xwməθkwəy̓əm (Musqueam), Skwxwú7mesh (Squamish), Stó:lō and Səl̓ílwətaʔ/Selilwitulh (Tsleil- Waututh) Nations.

Cover photos:

Row 1: (Left to right) Tyler Harper (Nelson Star), Dave Kasper (General Recycled), Dave Kasper (General Recycled)

Row 2: (Left to right) Fabio Scaldaferri (Mattress Recycling), Stock Photo, Recycled Cotton / Naia Fabric (Kendor Textiles)

Contents

Executive Summary 1
1.0 Introduction 3
2.0 Background 4
3.0 Scope and Methodology 5
4.0 Results 7
4.1 Methods for Emissions Estimation 7
4.1.1 Life cycle assessment (LCA) 7
4.1.2 Material flow analysis (MFA) 8
4.1.3 Environmental footprint 9
4.1.4 Eco-efficiency 10
4.1.5 Higg Index 11
4.1.6 Greenhouse Gas (GHG) Protocol Initiative - Corporate Standard, Scope 3 Standard, and Product Standard 12
4.1.7 Product Environmental Footprint (PEF) – Category Rules: Apparel and Footwear 15
4.2 GHG Emissions Estimations for End-of-Life (EOL) Scenarios 17
4.2.1 LCA Studies Comparing GHG Impacts of Various EOL Scenarios 19
4.2.2 GHG emissions calculations selected from GHG Protocol - Scope 3 Standard 21
4.3 Data Sources and Availability in Western Canada 24
4.4 Summary of Results 24
5.0 Industry Collaboration 26
6.0 Conclusions & Outlook 28
7.0 Recommendations & Next Steps 29
References 31
Appendices 34
A1 - Emissions estimation/modeling methods used for analyzing textile end-of-life scenarios 35
A2 - Resource Links 38

List of Figures

Figure 1. Flow of used/waste apparel generated yearly in Canada 4

Figure 2. Higg module coverage across apparel and footwear product value chain. Product Module which encompasses EOL processes is highlighted. (Reproduced) 11

Figure 3. GHG Protocol scopes (1-3), and examples of emissions across value chain. 13

Figure 4. Breakdown of % of total emissions by scope for companies with approved science-based targets. (Reproduced) 14

Figure 5. Relationship between Corporate, Scope 3, and Product Standards for a company manufacturing product A. (Reproduced) 15

Figure 6. Overview of standards, methods and tools used to support GHG emissions estimations in the textile and apparel industry. 18

Figure 7. Results from selected LCA studies: amount of CO_2 abated per tonne of textile waste, grouped by end-of-life scenario category. 19

Figure 8. Hierarchy of levels of data (least to most specific) that can be obtained for GHG emissions or activity estimates. (Reproduced) 21

Figure 9. Scope 3 emissions categories relevant to estimations for textile waste/EOL scenarios with calculation methods 23

List of Tables

Table 1. Inventory data types for emissions estimations 17

Table 2. Selected LCA studies that compared impacts of textile waste EOL scenarios 20

Table 3. Industry collaborations and organizations whose work covers textile waste management/EOL solutions 26

Executive Summary

The textile industry is a major contributor to global greenhouse gas (GHG) emissions and environmental impacts due to the complex supply chain involved in the production and global distribution of textiles. The industry's environmental impacts are expected to increase with the rising global demand for textiles. Textile and apparel waste is one of the fastest-growing waste streams worldwide, and efforts are being made to encourage responsible end-of-life management of discarded textiles and to reduce apparel waste. While end-of-life (EOL) stages of textiles contribute less to emissions compared to other value chain areas, proper management and diversion strategies can significantly reduce the industry's environmental impact. Emissions modeling to quantify the potential GHG savings of implementing various textile waste management strategies can help guide effective decision-making.

This report was prepared for the Textile Lab for Circularity through The University of British Columbia's Sustainability Scholars Program. The findings of this work contribute to the Textile Lab for Circularity's research project, *Roadmap to Textile Recycling for Western Canada*, which aims to inform strategic action planning to enhance textile diversion in the region, in particular mapping a path towards greater access to textile recycling. For this project, exploring the connection between alternatives to landfill and potential reductions in GHG emissions reductions is a key component of making the case for investment in diversion systems and infrastructure. The report provides a review of emissions modeling and estimation methods used to compare and assess environmental impacts of textile waste end-of-life management strategies in the industry. Case examples are compared, and general approaches for performing emissions estimations based on standards and guidance are provided. Industry collaborations that facilitate and bring together stakeholders to advance textile waste management strategies are highlighted. Studies reviewed have demonstrated higher environmental benefits of reuse strategies compared to current recycling options in the global market. From the research it has been found that the lack of primary inventory data, geographic spread, and challenges in tracking emissions across supply chain processes pose difficulties in accurately assessing environmental impacts of textile waste produced and thus assessing impacts of EOL solutions.

Research methods utilized in this work included a systematic literature review from peer-reviewed research, academic research, industry reports, and stakeholder interviews.

To advance the understanding of modeling environmental impacts of textile end-of-life solutions, the following recommendations and next steps are proposed:

- Employ greater reuse/repurpose/repair tactics to facilitate the transition towards circular economy strategies
- Collaboration between stakeholders (manufacturers, retailers/brands, waste management organizations, policymakers) to develop effective strategies for textile waste management, emissions modeling, and to share relevant data and findings
- Increased education and opportunities to support improved EOL management practices among industry and consumers
- Provide more guidance to industry on accessing and conducting life cycle assessments (LCAs) that incorporate end-of-life considerations
- Collect and organize data to perform emissions modeling for textile and apparel industry stakeholders in Canada (reuse/takeback programs, textile recycling plants, sorter/grader materials stream analysis)
- Foster digital solutions to streamline data collection among stakeholders
- Harmonize the textile & apparel categories that are assessed in municipal and regional waste composition studies
- Greater harmonization of emissions reporting to avoid duplication of efforts and enable comparisons across organizations and sector
- Western Canada/Canada-wide: Compile, isolate, and track textile waste materials stream inventory data for environmental reporting, and to enable future emissions modeling to be carried out

1.0 Introduction

The textile and apparel industry is the third-largest global manufacturing sector, with operations spanning multiple continents. The production and global distribution of textiles involves a complex supply chain that is closely linked to other global industries such as agriculture, natural resources, and chemicals. Consequently, the industry is a significant contributor to global greenhouse gas emissions and environmental impacts [1], [2]. The production and transportation stages are areas within the supply chain with the highest environmental impacts [3]. Significant impacts are from energy, water, and chemical use, textile waste, wastewater discharges, and transport emissions [3]. The global textile and apparel industry's environmental impacts are expected to increase unless it shifts away from business-as-usual, given the rising global demand and consumption of textiles.

Textile and apparel waste is estimated to be one of the fastest growing waste streams globally, owing to the rise of fast fashion, mass production of apparel at low-cost, and rapid trend cycles all spurring high clothing consumption. It is estimated that textile waste accounts for approximately 5% of total waste worldwide (in landfill) [4]. Efforts to encourage responsible end-of-life management of discarded textiles, reduce apparel waste, and promote the diversion of used/waste apparel are gaining global momentum as the impacts of the textile and apparel industry are increasingly recognized.

This report provides a review of emissions modeling and estimation methods used to assess environmental impacts of end-of-life strategies in the textile and apparel industry. Methods are evaluated and relevant case studies are presented. The review of methods applies for the wider umbrella of both textiles and apparel, although the case studies focus on apparel waste streams specifically. General approaches for performing emissions estimations are presented, which offer a guide for future comparative analyses of end-of-life solutions.

The findings of this work contribute to the Textile Lab for Circularity's research project, *Roadmap to Textile Recycling for Western Canada*, and aim to inform strategic action planning for GHG emissions reduction and developing end-of-life diversion programs in the textile and apparel industry.

2.0 Background

Emissions modeling and estimation are crucial in the textile and apparel industry to examine major sources of GHG emissions within the supply chain, and to identify actions and solutions to reduce sector emissions. Assessing data sources and modeling/estimation methods can facilitate greater accountability and transparency, leading to the acquisition of reliable data to continuously monitor processes and inform environmental reporting.

While the proportion of emissions associated with the end-of-life stages of textiles may be lower compared to other value chain areas in the textile and apparel industry, proper management, and diversion strategies such as repair, reuse, and recycling can help to reduce the industry's environmental impact through offsetting virgin textile production and facilitating the transition towards more circular practices. In assessing emissions at end-of-life, the lack of or incomplete primary inventory data, geographic spread, along with difficulties in tracking sold products after consumer use, has shown to result in broad assumptions made in emissions estimations when assessing environmental impacts of EOL solutions for textiles and apparel.

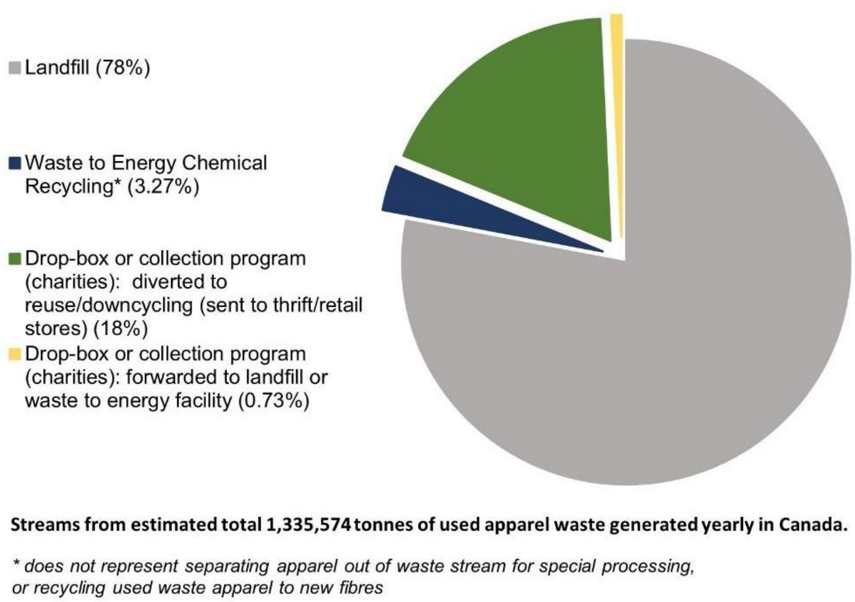


Figure 1. Flow of used/waste apparel generated yearly in Canada [5].

In Canada, an estimated 1.3 million tonnes of used textile waste are generated annually, which flow through various waste streams, with approximately 18% diversion (Figure 1). The majority of waste (approximately 1 million tonnes) is sent to landfills, which represents lost opportunities for waste reduction and valorization. Introducing effective end-of-life strategies for textile waste diversion can reduce emissions, meet sustainability targets, and bring economic benefits through increased resource efficiency and new revenue streams. To guide effective decision-making and better understand the impacts of implementing waste management strategies, emissions modeling can be performed to accurately compare and quantify potential GHG savings.

3.0 Scope and Methodology

The aim of this research was to identify key methods and criteria used to evaluate and assess greenhouse gas emissions and reduction potential from varying end-of-life management scenarios for textiles, with an initial emphasis on understanding the comparative greenhouse gas emissions between recycling and landfilling. The initial scope of this work involved identifying best practices and methods for emissions modeling and estimations with the intent to generate a comparative analysis of emissions across textile waste end-of-life solutions in Western Canada. However, upon conducting a literature review and industry data scan, it was found that there is limited primary data available on textile waste and tracking of end-of-life strategies employed, hindering the generation of accurate emissions estimates for the industry in Western Canada.

Therefore, an initial review was performed to investigate methodologies used to measure and monitor environmental impacts of products or processes in the textile and apparel industry. Methods with precedent for use in the assessment of emissions from end-of-life scenarios were selected and relevant case examples were reviewed to generate a comparative analysis of impacts. In addition, calculation methods and data requirements for general estimations related to the assessment of end-of-life scenarios were summarized.

In this work, textile waste streams considered from the research reviewed include ‘pre-consumer’ (or post-industrial), and ‘post-consumer’ waste. Pre-consumer waste includes materials (scraps, offcuts, samples, damaged materials, etc.) that arise from the production stage processes. Post-consumer waste includes materials or products that have been used by the consumer (discarded garments, household textiles, etc.). Textile end-of-life (EOL) solutions identified from the sources included: reuse/repair/reduce, textile recycling (mechanical or chemical), energy recovery through incineration, and landfilling.

A systematic review was carried out by searching databases and grey literature for peer-reviewed journal articles and reports. Databases and grey literature sources included: Scopus, Web of Science, Science Direct, Google Scholar, and Internet Archive. Keywords searched in combination included: textile, apparel, clothing, garment, sustainability assessment, life cycle analysis, environmental assessment, carbon emissions, emissions, assessment, evaluation, textile recycling, landfill, incineration, reuse. From database literature search articles scanned, five emissions assessment methods were identified: life cycle assessment (LCA), environmental footprint (includes carbon, chemical, water footprint), eco-efficiency, material flow analysis, and Higg Index. Relevant industry reports, guidance, and standards were found through internet searches.

4.0 Results

4.1 Methods for Emissions Estimation

The following methods identified for greenhouse gas emissions estimations used in the textile and apparel sector are described in this section.

- Life cycle assessment (LCA)
- Material flow analysis (MFA)
- Environmental footprint
- Eco-efficiency
- Higg Index
- Greenhouse Gas Protocol Initiative – Corporate Standard, Scope 3 Standard, Product Standard
- Product Environmental Footprint (PEF) – Category Rules: Apparel and Footwear

More examples of their use in the context of textiles and apparel end-of-life are summarized in Appendix Table A.1.

4.1.1 Life cycle assessment (LCA)

LCA is a well-established and comprehensive methodology used to evaluate the environmental impacts of a product (or service) through its entire lifecycle, from raw materials extraction to disposal of the final product (or cradle to grave) [6]–[8]. LCA can be used to make decisions related to product design, process improvement, and to guide policy. They can provide a full streamlined analysis of environmental impacts based on the level of detail selected for a chosen scope. LCAs are widely used for estimating GHG emissions, with standardized methodology to carry out the analysis, and have the potential to be highly accurate based on data quality. Various standards have been developed to organize LCAs, with ISO 14040 and 14044 (ISO 14040: Environmental management — Life cycle assessment — Principles and framework; ISO14044: Environmental management — Life cycle assessment — Requirements and guidelines) being the most referred to standards for conducting and reporting an LCA. However, the method is data intensive, time-consuming, requires expert knowledge to carry out, and often expensive to conduct.

An LCA typically involves four main phases [6]:

-Goal and scope definition: objective, system boundaries, processes/activities of the system, and functional units are defined

-Inventory analysis: process flow charts, inputs and outputs for process steps are collected and organized (energy, material, emissions, waste flows), with data processed by classification, characterization, weighting

-Impact assessment: can be expressed at two levels – midpoint (based on impact categories of inventory substances such as global warming potential, water use, primary energy use, etc.) and endpoint (damage categories which include damage to mineral and fossil resources, ecosystem quality, human health)

-Interpretation: analysis of inventory and impact assessment carried out to draw conclusions and provide recommendations based on goal and scope of the study; identification and evaluation of significant impacts associated with the system being assessed, sources of uncertainty, limitations of analysis, trade-offs

4.1.2 Material flow analysis (MFA)

MFA is a systematic assessment method that quantifies the state and changes of material flow and stocks/substances within a system defined in space and time [9]. It tracks material sources, pathways, intermediates to the final sink of a finished material. Reported results consist of a mass balance of all inputs, stocks, and outputs of process(es). MFA can be used to identify resource inefficiencies within a particular system, give a better understanding of environmental impacts by tracking material flows, help to improve resource management, and present opportunities to use resources more efficiently. Challenges in using MFA include the need for accurate and comprehensive data (material inputs and outputs), potential for assumptions and simplifications to be made, scope limitations outside of material flows, and specialized knowledge and skills to be implemented effectively. MFA involves the following steps [9], [10]:

-Define aim and scope (geographical, temporal)
-Identify system boundaries
-Define baseline and prospective scenarios
-Determine and describe data sources (material flow, stocks),
assumptions, material balances
-Interpretation

4.1.3 Environmental footprint

Environmental footprinting is a methodology that combines elements of life cycle assessment (LCA) to estimate various independent indicators of environment impact, such as ecological, water, carbon, and chemical footprints [11]. In the textile and apparel industry, carbon, water, and chemical footprints are frequently assessed. Standard methods have been developed to facilitate environmental footprint calculations. This methodology can provide a clear understanding of the environmental indicator being analyzed, enabling targeted efforts for emissions reduction and operational efficiencies. However, environmental footprinting requires careful consideration of data availability and type, has a high level of complexity based on the specificity of the indicators being analyzed, and uncertainties due to the assumptions made in the calculations. The method involves the following general steps [12], [13]:

-Identification of type of footprint
-Definition of scope and processes
-Identification of system boundaries
-Equations and calculations for footprint determination

Carbon footprint analysis involves the quantification of GHG emissions, with various calculations formulated by standards organizations (BSI PAS 2395:2014 Specification for the assessment of greenhouse gas (GHG) emissions from the whole life cycle of textile products). The general calculation is expressed as follows [11]:

$$CF = \sum_{i=1}^{n} \sum_{i=1}^{m} AD_i \times ef_{ij} \times GWP_j$$

where CF is carbon footprint in kg AD_i is activity data of emission source i, GWPj is global warming potential of GHG j, measured by the atmospheric environment mechanism model [14].

Water footprint analysis is used to measure environmental impacts related to water quality and water resources. Two main accounting approaches are taken: Water Footprint Network (WFN), and ISO14046:2014 Environmental management-water footprint principles, requirements, and guidelines. WFN includes quantification methods that describe water consumption and water pollution [15]. ISO14046 quantifies water availability in terms of water scarcity footprint, and water degradation in terms of indicators that include water eutrophication, acidification and ecotoxicity footprint [16].

Chemical footprinting is used for the quantification of potential environmental hazard of chemicals. The calculation is expressed as [11]:

$$ChF = \sum_{j=1}^{8} \sum_{i=1}^{n} CF_{i,j} \cdot M_{i,j}$$

where ChF is chemical footprint; $Cf_{i,j}$ is the characterization factor of chemical pollutant *i*, emitted into environmental compartments defined by *j*, and M_{ij} is the mass of a chemical pollutant (*i*) emitted into environmental compartment *j*.

For human toxicity, ChF represents the number of pathogenic cases caused by a unit of chemical (cases/$kg_{emitted}$) [17].

For ecotoxicity, ChF refers to an estimate of the potentially affected fraction of species over a given time and volume, per unit mass of a chemical emitted (m^3day/$kg_{emitted}$) [18], [19].

Collecting data and quantifying the chemical footprint of textile and apparel products is challenging due to the varied use of chemical raw materials in production, as well as the complexities involved in detecting chemical pollutant discharge [11], [20], [21].

4.1.4 Eco-efficiency

Eco-efficiency combines environmental and economic performance to assess products, processes, or systems within an enterprise or industry setting. In textiles and apparel, it is often used for environmental sustainability evaluation at enterprise and product levels [11]. The method integrates life cycle assessment principles from which general considerations into the impacts of a product or process lifecycle is assessed. It can be used to identify opportunities to improve environmental emissions/impacts and efficiencies and inform decision-making around resource allocation, process design, and sustainability measures. However, like the other methods outlined, the method requires careful consideration of data selection, scope, and assumptions.

The eco-efficiency ratio is defined by the World Business Council for Sustainable Development (2000) as follows [11], [22]:

$$eco - efficiency = \frac{economic\ value\ of\ a\ product\ or\ service}{environmental\ impact\ of\ a\ product\ or\ service\ creation}$$

The economic value/factor is often expressed as monetary value (e.g., sales revenue) or physical quantities (e.g., yield) and the environmental impact/factor associated with resource input and waste output for a process (e.g., water, energy, material consumption, wastewater, greenhouse gas emissions), which can be quantified from LCA.

The impact of multiple environmental indicators can be combined into a single comprehensive index as follows:

$$eco - efficiency = \frac{economic\ indicator}{\sum \quad environmental\ indicators}$$

4.1.5 Higg Index

The Higg Index suite of assessment (product, facility, brand levels) for apparel and footwear products was developed by the Sustainable Apparel coalition (SAC). The tools cover environmental and social impact analyses allowing brands, retailers, and manufacturers to conduct self-assessments on product sustainability [1], with results reported on a scale from 0 to 100 [11], [23].

The Higg Product Tools comprise the Higg Material Sustainability Index (MSI), and Higg Product Module (PM), which follow an LCA approach to analyze environmental impacts of a product across its lifecycle (raw materials extraction to end-of-life disposal) [1], [23]. The Higg Materials Sustainability Index covers raw material extraction to production phases with data sourced from industry and LCA databases, while the Higg Product Module covers finished production and assembly goods to end-of-life processes [24] (Figure 2).

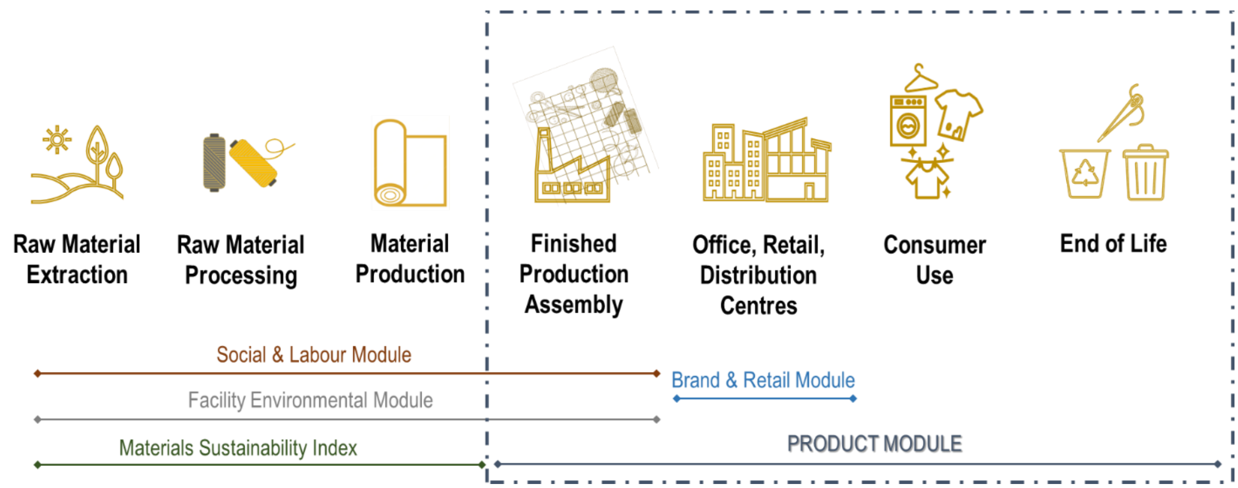


Figure 2. Higg module coverage across apparel and footwear product value chain. The Product Module which encompasses EOL processes is highlighted. Reproduced from [1].

Five environmental impact categories are covered which include global warming potential, eutrophication, water scarcity, fossil fuel depletion, and chemistry [24]. The Product Tool offers a standardized approach to evaluating the environmental impacts of products for organizations, provides insights to making informed decisions around material sourcing, design and manufacturing, and promotes collaboration across the value chain (suppliers, brands).

Like other analysis methods, accuracy in impacts assessed are dependent on data quality and availability. The tool also requires a fee to access and use, which may be a barrier for smaller brands. Use of the Higg MSI data in a piloted Higg Index Transparency Program has been critiqued for the misrepresentation of environmental attributes for material comparisons in consumer-facing environmental claims, potential biases in the methodology and not adequately accounting for the full environmental impacts of a material/product [25]–[27]. The index data and methodology are currently under third-party review [28].

4.1.6 Greenhouse Gas (GHG) Protocol Initiative - Corporate Standard, Scope 3 Standard, and Product Standard

The GHG Protocol Initiative was established by the World Resources Institute, World Business Council for Sustainable Development, and corporate partners, and is a multi-stakeholder collaboration of businesses, non-government organizations, and government [3], [29]. It aims to develop an internationally recognized GHG accounting and reporting framework for businesses and government [3], [29]. GHG Protocol publishes several standards and guidance documents, three of which are selected here for relevance to end-of-life GHG analyses: the Corporate Accounting and Reporting Standard, the Corporate Value Chain (Scope 3) Standard, and the Product Standard.

The GHG Protocol Corporate Accounting and Reporting Standard (referred to as the Corporate Standard) was developed to provide requirements and guidelines for companies and organizations worldwide to quantify and report GHG emissions. The Standard defines emissions under three scopes (Figure 3) [29]:

Scope 1 (required reporting): Direct GHG emissions (GHG specified by Kyoto Protocol) from sources owned and operated by a company. Examples: combustion from company-controlled furnaces, vehicles, emissions from company's process equipment

Scope 2 (required reporting): Indirect emissions from the generation of purchased electricity consumed by the company. Example: calculated emissions from facility electricity use

Scope 3 (optional reporting): Indirect GHG emissions that are a consequence of company activities that occur from sources that are not owned or controlled by the company. Examples: transport, distribution, and use of finished or sold products and services, waste disposal of used or purchased goods.

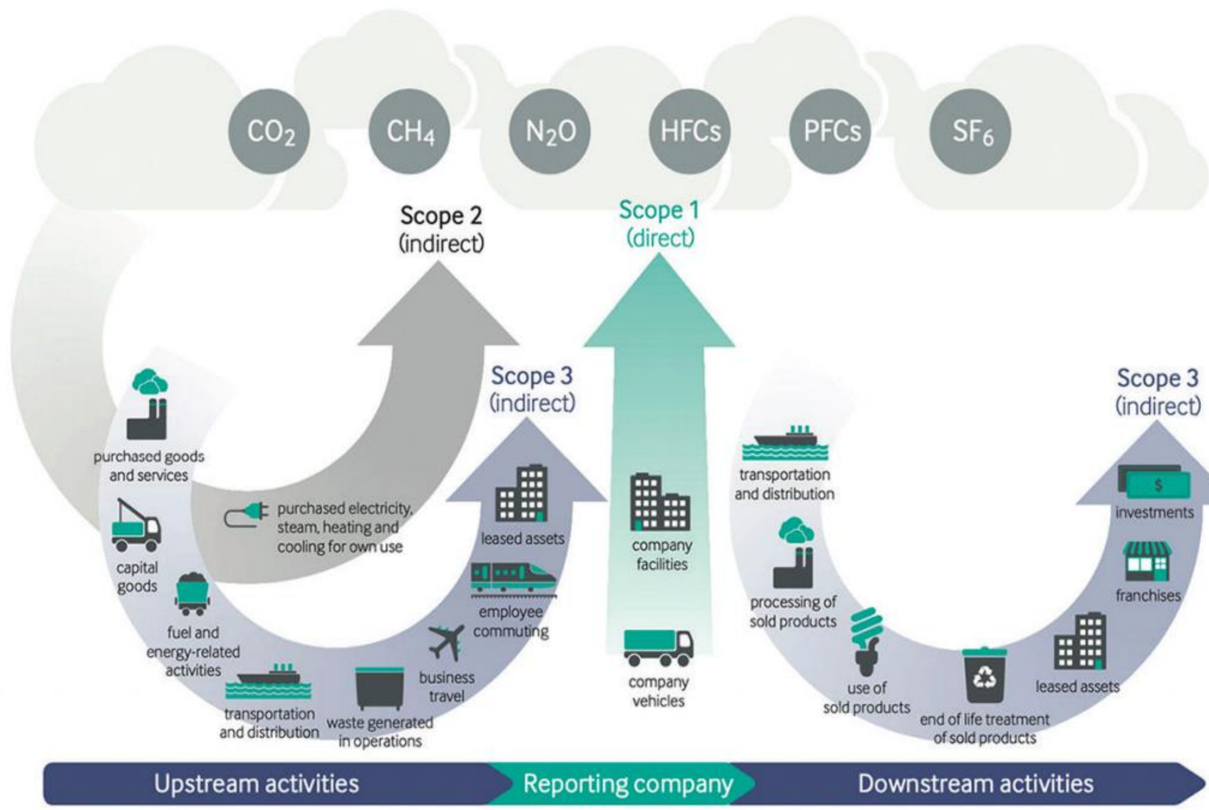


Figure 3. GHG Protocol scopes (1-3), and examples of emissions across value chain [29].

In the context of the textile and apparel industry, Scope 1 and 2 emissions constitute a larger proportion of emissions for upstream suppliers (textile and apparel manufacturers). For consumer-facing brands and retailers that typically have a large supply chain network and rely on external suppliers, Scope 3 emissions often constitute a significant majority of their total emissions (Figure 4). Measuring and managing Scope 3 emissions poses a challenge for brands and retailers due to limited or no access to detailed data on emissions from upstream suppliers and waste management. This results in limited insight into the accuracy of emissions produced in supply chain activities, which can impede the ability of brands and retailers to set and track meaningful emissions reduction targets, and make procurement decisions informed by such targets.

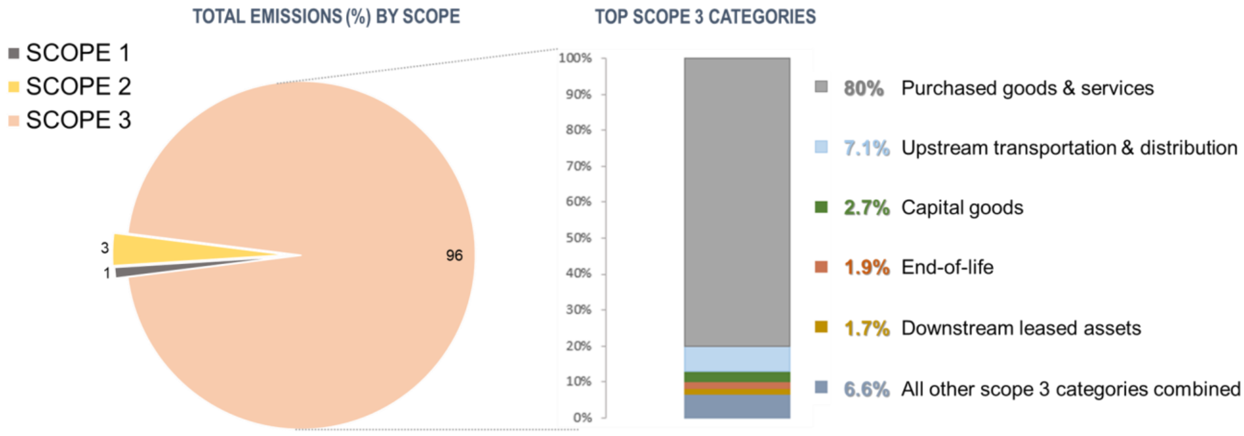


Figure 4. Breakdown of % of total emissions by scope for companies with approved science-based targets (Science-Based Targets Initiative – SBTi). Reproduced from [1].

The GHG Protocol Corporate Value Chain (Scope 3) Standard (referred to here as Scope 3 Standard) provides requirements and guidance for organizations on calculating indirect emissions in their value chains. The standard provides a comprehensive approach to indirect emissions accounting and includes calculation methods and guidance for activities such as emissions from purchased goods and services, transportation and distribution, use of sold products, and waste disposal. The Scope 3 Standard comprises 15 categories covering upstream and downstream emissions categories. This can enable organizations to identify opportunities for GHG emissions reduction across their corporate value chain. [30]

The GHG Protocol Product Standard (referred to as Product Standard) provides requirements and guidance for organizations to quantify and report GHG emissions and removals (i.e., extractions and storage of GHG from the atmosphere) associated with a product's lifecycle using the LCA approach. The standard enables organizations to understand the impact of their products, compile inventory data, and identify opportunities to reduce emissions through informed decisions about product design, procurement, and manufacturing, which can also be communicated to stakeholders. [31]

These three GHG Protocol standards can be used together to inform GHG-reduction strategies from product to corporate level (Figure 5). The Product Standard may be used to calculate scope 3 emissions of a product type. The Corporate and Scope 3 Standards can be used to determine the total emissions and identify products with high emissions, from which the Product Standard can be used to identify mitigation opportunities. [31]

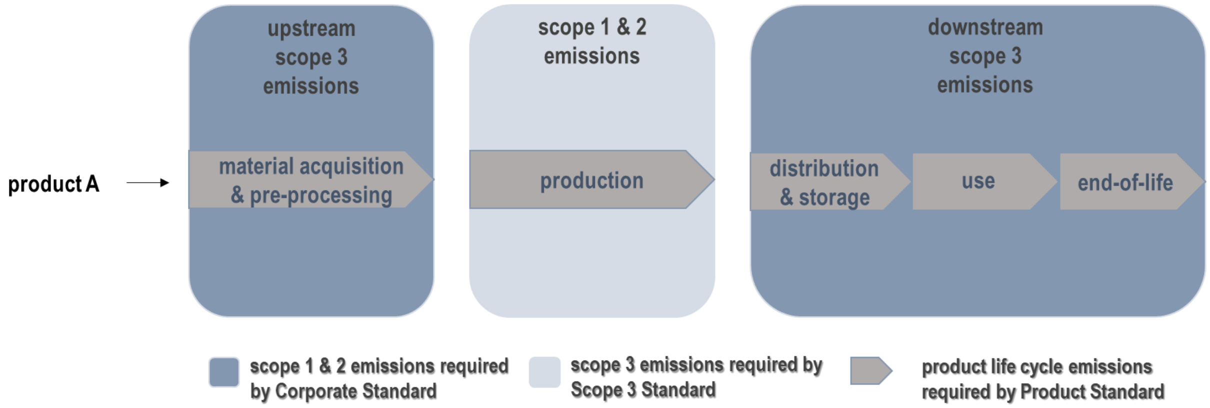


Figure 5. Relationship between Corporate, Scope 3, and Product Standards for a company manufacturing product A. Reproduced from [31].

The GHG Protocol standards have limitations such as only focusing on GHG emissions, which may not provide a complete understanding of a company's environmental impacts. Data availability and quality may vary and affect the accuracy of the results reported. Additionally, potential variability in how organizations choose to implement the standards which can limit comparability.

4.1.7 Product Environmental Footprint (PEF) – Category Rules: Apparel and Footwear

The Product Environmental Footprint (PEF) is a harmonized methodology developed by the European Commission for carrying out environmental footprint studies to measure the environmental impact of products throughout their lifecycle [32]. It was developed based on existing approaches and standards (including ISO 14040 series LCA, GHG Protocol, ISO 14067 Greenhouse gases - Carbon footprint of products, etc.), and aims to provide better reproducibility and comparability between product impact assessment through industry specific Product Environmental Impact Category Rules (PEFCR) [33], [34]. PEFCR are technical rules for carrying out environmental assessment of products sold or consumed in the EU, UK, and EFTA [32]. The methodology uses the lifecycle approach and method and provides guidance for calculating impacts at all stages of the product value chain (full lifecycle or partial lifecycle impact can be carried out), from raw material extraction to end-of-life disposal [23], [35], [36]. The Product Environmental Footprint (PEF) Category Rules for Apparel and Footwear (draft) is an application of the PEF methodology that has been developed through a collaborative process involving industry stakeholders, environmental experts, and policymakers, in the textile and apparel industry, and is currently in the development phase [33].

The PEF for apparel and footwear considers a wide range of products and materials as well as LCA environmental impact categories. Comprehensive guidance is provided on how to collect and analyze data across the product's life cycle. The PEF is expected to serve as an important reference in the European Union's efforts to promote sustainable consumption and production and support industries in the transition to a circular economy [34], [37]. Challenges associated with the PEF include complexities in the collection (availability and quality) and selection of data, variability in selecting which environmental impacts to include, and weighting for different impact categories [36].

4.2 GHG Emissions Estimations for End-of-Life (EOL) Scenarios

In the textiles and apparel industry, the techniques most used to assess GHG emissions for textile waste end-of-life (EOL) scenarios are LCA and LCA-related standards, guidance methods and tools. A general overview of all reviewed standards, methods and tools used to support EOL GHG emissions estimations in the industry are presented in Figure 6, then the following approaches to understanding impacts of textile EOL management strategies are presented:

- Results from LCA studies comparing textile end-of-life scenarios that can serve as baseline comparisons for future modeling work and inform strategy or policy decisions related to textile waste management, and circular economy initiatives.
- Streamlined GHG emissions calculations selected from GHG Protocol guidance.

Both LCA and GHG Protocol methods specify data requirements for process analysis. Primary data refers to raw data that is directly measured and collected from activities occurring in facilities [29], [34]. The use of primary data is preferred as it allows for more accurate and specific assessments and enables companies to have greater ownership over their emissions analysis [34], [38]. However, it is often challenging and time-consuming to collect, and may require access to proprietary information. Secondary data refers to existing data sourced from third-party lifecycle inventory databases. The data may include averages or typical values for inputs or outputs of processes and products. While secondary data use may simplify the data collection process, it may not provide an accurate representation of the environmental impacts of the specific product or process being assessed. Table 1 presents an overview of data types and calculation factors with descriptors and examples.

Table 1. Inventory data types for emissions estimations [31]

DATA TYPE	DESCRIPTION	EXAMPLES
DIRECT EMISSIONS DATA	direct monitoring, mass balance calculations	-kg CO_2 from incinerator -fugitive refrigerant emissions (mass balance)
ACTIVITY DATA	measured, modeled, calculated (process or financial)	-km of distance traveled -volume of chemical -kg waste generated -$ spent
EMISSION FACTORS	GHG emission per unit activity data (multiplied by activity data)	-kg CO_2 emitted /km travelled by ship -kg CO_2 emitted /t cotton fibre produced -MJ heat/t waste
GLOBAL WARMING POTENTIAL (GWP) FACTORS	radiative forcing impact of 1 unit of a given GHG relative to 1 unit of CO_2	CO_2 has index value of 1, other gases are calculated with respect to CO_2 (i.e. methane is 28)

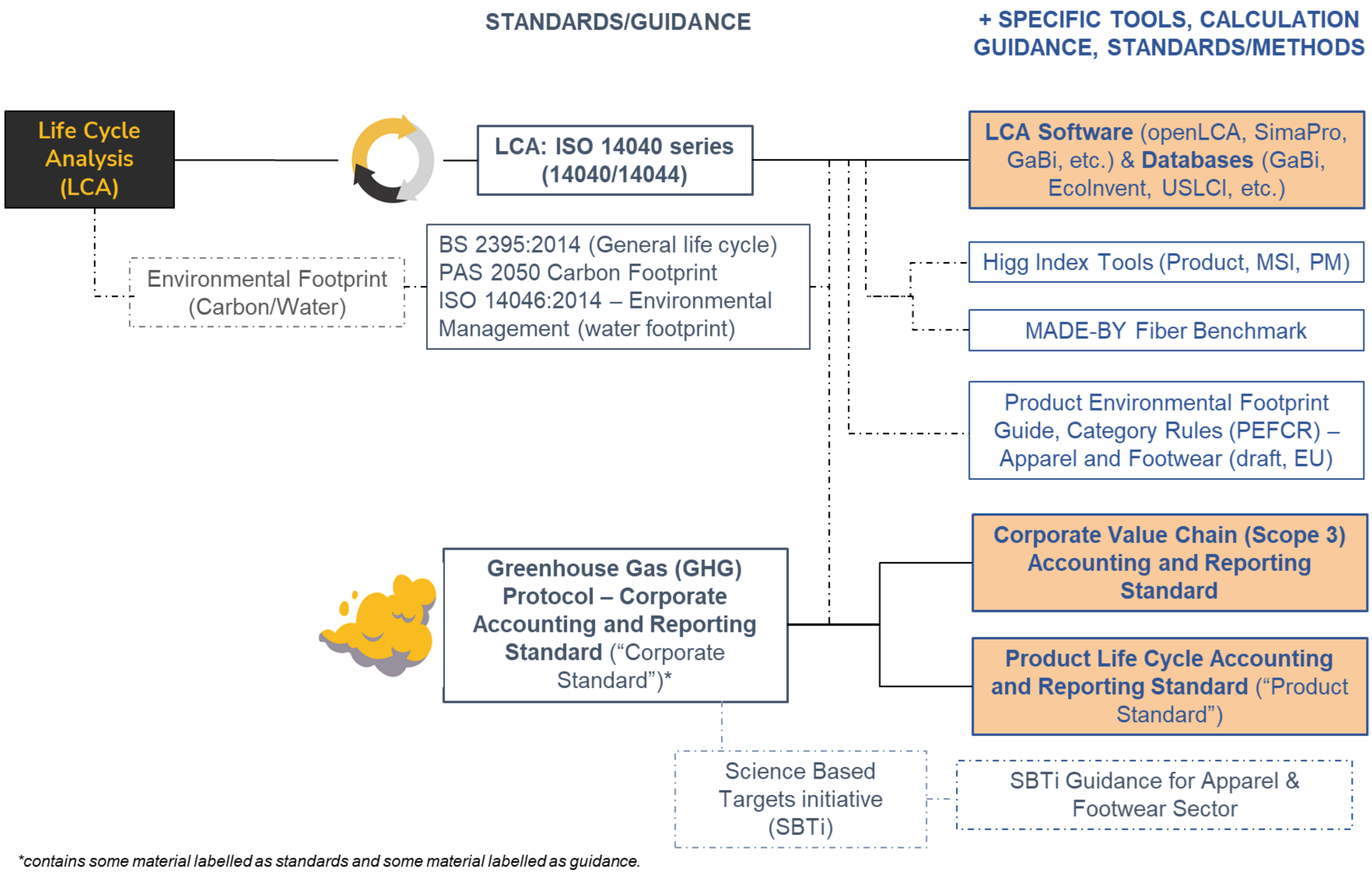


Figure 6. Overview of standards, methods and tools used to support GHG emissions estimations in the textile and apparel industry.

4.2.1 LCA Studies Comparing GHG Impacts of Various EOL Scenarios

From the literature review, five LCA studies that examined and compared the impacts of end-of-life (EOL) scenarios were selected with results summarized in Figure 7 and Table 2. The EOL management scenarios covered in the studies included reuse, recycling (mechanical, chemical, thermal), landfill, incineration, and mixed scenarios. Selected results reported from these studies were recalculated where necessary to express equivalent CO_2 abatement (or savings) in tonnes per tonne of textile waste (t CO_2 abated / tonne of textile waste). This allowed for comparison across the scenarios investigated, given that the level of complexity of processes and data varied across the studies. The CO_2 emissions savings fall within a consistent range of values across the compared studies, providing a valuable reference point for future estimations. In addition, the results demonstrate the higher environmental benefits of reuse compared to recycling options in the global market. Furthermore, it is also of interest to note the differences in CO_2 abatement for various fibre types for a given EOL scenario. For example, the chemical recycling of 100% cotton or cotton blend textiles showed a lower rate of CO_2 abatement than recycling of 100% polyester textiles. It is expected that as textile recycling technologies are scaled up and continue to be adopted, there will be further increase in CO_2 savings in the future. Future waste management strategies are likely to involve mixed EOL scenarios which incorporate a combination of reuse, recycling, incineration, and landfilling.

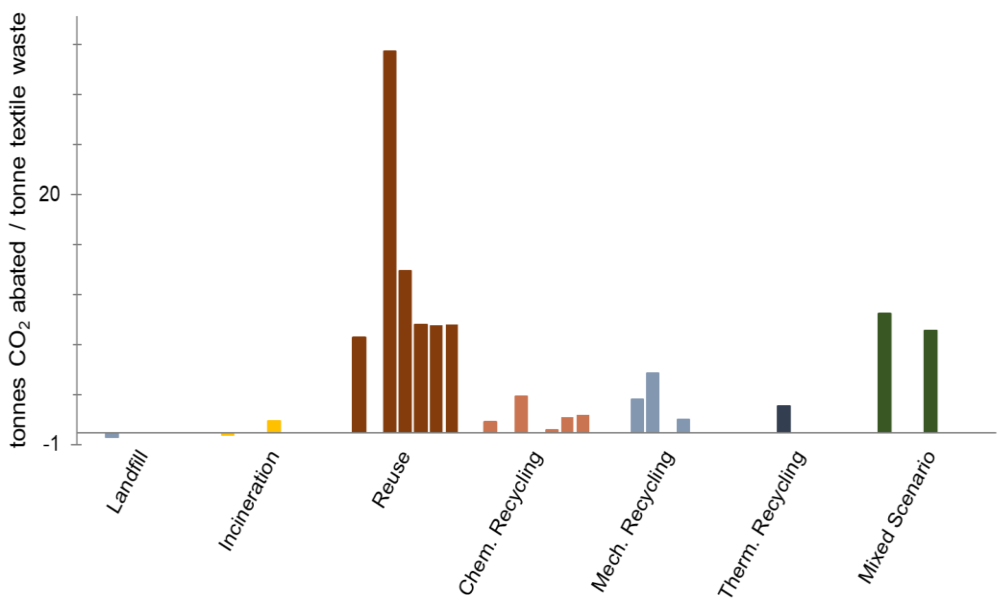


Figure 7. Results from selected LCA studies: amount of CO_2 abated per tonne of textile waste, grouped by end-of-life scenario category. (Note that not all studies compared the same combination of scenarios)

Table 2. Selected LCA studies that compared impacts of textile waste EOL scenarios *(* indicates that results were recalculated to enable comparison)*

Study Title (Author, Year)	Waste Composition	EOL Scenario	CO_2 Abated (tonnes CO_2e/tonne waste)
A Carbon Footprint of Textile Recycling: A Case Study in Sweden (Zamani et al., 2015) [7]	50-50 cotton-polyester	reuse	8.0
		incineration	-0.2
		chemical recycling	0.9
		integrated system (reuse, recycle, incinerate)	10.0
Exploring an alternative to the Chilean textile waste: A carbon footprint assessment of a textile recycling process (Perez et al., 2022) [39]	33.63% cotton, 58.73% polyester, 7.63% wool	landfill	-0.4
		mech. recycling	5.8
Greenhouse Gas Emission Reductions by Reusing and Recycling Used Clothing in Japan * (Semba et al., 2020) [40]	100% cotton	reuse overseas	32.0
	100% cotton	mech. recycling (wipers)	3.3
	various (wool, polyester, cotton, acrylic)	mech. recycling (reclaimed fibre felt)	6.7
	100% polyester	chem. recycling (Teijin)	3.1
	100% polyester	thermal recycling	2.2
Environmental Assessment of End-of-Life Textiles in Denmark (Koligkioni et al., 2018) [41]	56% cotton, 44% polyester	reuse in Denmark	15.4
		reuse in Europe	12.5
		reuse in rest of world	12.8
		incineration	1.0
		mixed scenario (incineration, reuse)	8.6
LCA-based assessment of the management of European used textiles * (EurRIC Textiles, Norion Consult, 2023) [42] *Report uses functional unit of 1 t-shirt, 155g – results converted to 1 tonne textile waste* *+RR: degree to which second-hand clothing/textile purchase replaces purchase of similar new items*	100% cotton	reuse, 10% replacement rate (RR+)	1.8
		reuse, 40% RR	8.4
		reuse, 80% RR	17.1
		mech. recycling (to fibres to be respun)	1.1
		chem. recycling (avoided sulfate)	-0.2
		chem. recycling (avoided sulfite)	0.6
	30/70 polycotton	reuse, 10% RR	0.9
		reuse, 40% RR	8.2
		reuse, 80% RR	17.9
		chem. recycling (to cellulose, PET)	1.2
	100% polyester	reuse, 10% RR	1.5
		reuse, 40% RR	8.3
		reuse, 80% RR	17.5
		chem. recycling (to monomers → PET)	1.5

4.2.2 GHG emissions calculations selected from GHG Protocol - Scope 3 Standard

The GHG protocol standards and guidance provide general means of quantification through either direct measurements, or calculations based on emission factors (appropriate to context), activity data, and global warming potentials. In assessing which methods in the GHG Protocol standards are most applicable to end-of-life (EOL) analysis, the most relevant EOL GHG calculations can be extracted from the Scope 3 Standard guidance. In EOL scenarios, the data selected for analysis generally come from facility, activity-/process-/production-line, and product levels (Figure 8).

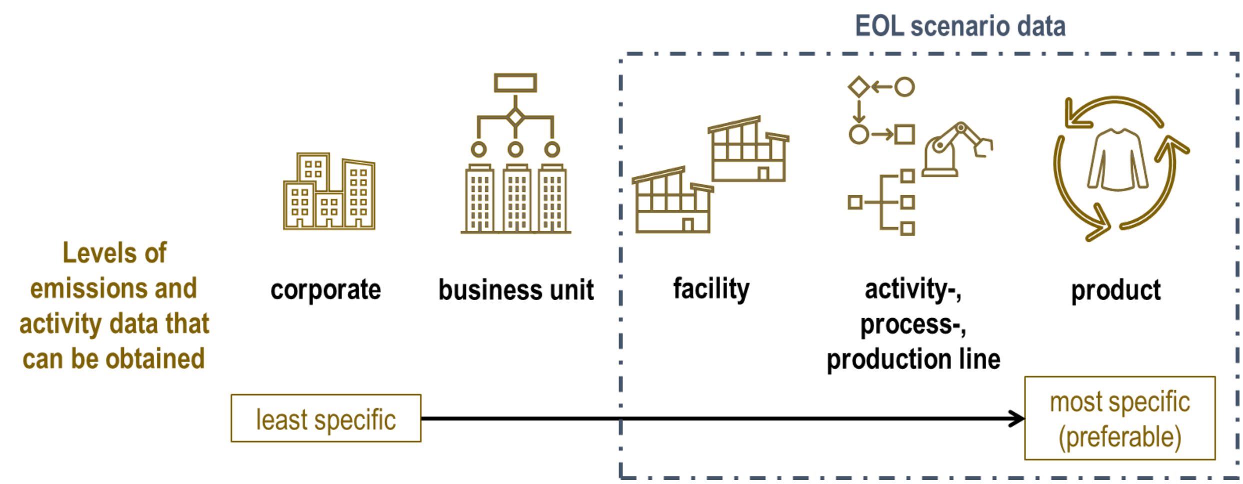


Figure 8. Hierarchy of levels of data (least to most specific) that can be obtained for GHG emissions or activity estimates. Reproduced from [30].

Within the Scope 3 Standard, upstream and downstream categories relevant to EOL management of textiles waste have been identified for consideration and are presented in Figure 9. The two categories cover emissions from waste generated in operations (category 5), and end-of-life treatment of sold products (category 12). Calculation methods provided in the standard are also included. Specific data collection and calculation guidance with examples are provided in the Scope 3 standard (Category 5: page 72-80; Category 12: page. 125-127 [30]). Case examples of how each of these two categories are reported by textile and apparel brands utilizing the Scope 3 Standard are presented.

Category 5 emissions are often generated from third-party disposal or waste companies, and as a result, this data would constitute those companies' scope 1 and 2 emissions. However, in the case where this data cannot be obtained, the standard provides guidance for alternate calculations based on waste tonnage and emission factors specific to the waste treatment method. [30]

Case example, Category 5 – Prada Group [43]

Scope 3, Category 5 emissions consider disposal/recycling of waste generated by their manufacturing sites. Calculations are made from secondary data.

Activity data – kg waste disposed or recovered

Emission factor (2019-2021): DEFRA (Department of Environment, Food & Rural Affairs), Conversion factors - Full set, 2019, 2021

GWP-100: CO_2 equivalent

Category 5 - Waste generated in operations, Total: 2,316 t CO_2e

Category 12 emissions include EOL treatment of sold products, which can be more difficult to track and calculate. As a result, the calculation guidance specifies the use of average data calculations, considering the total mass of sold products and packaging from the point of sale (POS). In cases where a retailer or brand has a takeback program and a trackable textile waste treatment process, it is possible to obtain more comprehensive and accurate emissions calculations for this reporting category. [30]

Case example, Category 12 – Nike Inc. [44]

Scope 3, Category 12 emissions are associated with the disposal of products including landfill and incineration. Calculations are made from secondary data.

"There is no primary emissions data available for end-of-life treatment of NIKE's products. To evaluate NIKE's value chain footprint, we identified and quantified CO2e emissions created at each stage of the value chain. The impact of each individual product differs considerably, based on its profile, materials used, size and weight, method of manufacture, and location of production, use and disposal. Several internal and external tools were used to develop this estimation including Enablon, NIKE's Materials Sustainability Index and EPA's Waste Reduction Model (WARM). End of Life Stage: at the disposal stage we assumed the finished good is disposed of at the end of one year."

Category 12 – End-of-Life Treatment of Sold Products, Total: 418,080 t CO_2e

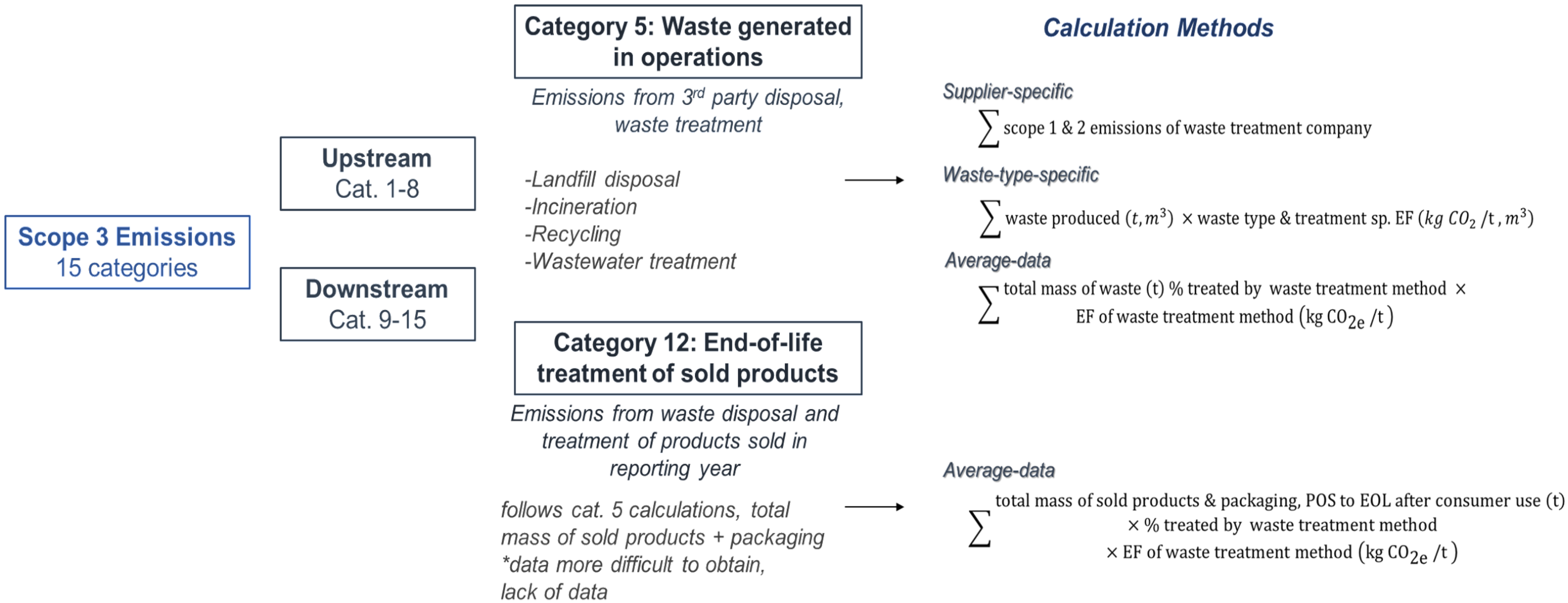


Figure 9. Scope 3 emissions categories relevant to estimations for textile waste/EOL scenarios with calculation methods [30].

4.3 Data Sources and Availability in Western Canada

From stakeholder interviews it was evaluated which information is most and least readily available in Western Canada. What follows is an initial, high-level summary of the data points that can be collected across sectors to better feed into modeling scenarios for this region. Of these, there is inconsistent granularity and quality of data across both public and private players.

- Transfer station data — waste composition, disposal / flow-through tonnages
- Landfill data — waste composition, tonnage and textile waste proportions
- Waste disposal tonnages from manufacturers
- Waste disposal tonnages from retailers
- Waste management tonnages from processors diverting material from landfill to other avenues, e.g., fibre reclamation
- Charitable sector material flow-through and disposal

As there is no currently operating mechanical nor textile recycling processes in Western Canada, the data for a comparative analysis of EOL scenarios which incorporates recycling would require the use of data from other regions.

4.4 Summary of Results

This section summarizes the use of life cycle assessment (LCA) related standards, methods, and tools for assessing greenhouse gas (GHG) emissions in the textiles and apparel industry, particularly for textile waste end-of-life (EOL) scenarios. GHG Protocol standards and guidance relevant to EOL analysis are highlighted, including the upstream and downstream categories that pertain to the management of textile waste, and provides specific data collection and calculation guidance with examples.

The initial scope of this work involved identifying best practices and methods for emissions modeling and estimations sufficient to generate comparative analysis of textile waste end-of-life solutions in Western Canada. Upon conducting a literature review and industry data scan it was found that there is limited primary data available on textile waste and tracking of end-of-life strategies employed, hindering the generation of accurate emissions estimates for the industry in Western Canada. This study instead sets out to explain the landscape for conducting these comparative analyses, with the intent to seed future work in this area.

Several challenges exist in modeling the impacts of textile waste end-of-life strategies. In general, there is a lack of primary inventory data for collection, sorting, and recycling processes. Assumptions are often made regarding the scope of end-of-life solutions, namely using industry-average emission factors. Additionally, for brands and companies looking to model indirect scope

3 emissions in their supply chain, activity data may not be available from partners and suppliers, which makes accurate emissions estimates difficult. It has been found that brands and retailers use varied methods for GHG protocol reporting, particularly in scope 3 emissions covering EOL categories, due to limited data availability. Another challenge is the uncertainty around the selection and configuration of recycling techniques for emissions modeling of textile recycling solutions, which are influenced by input composition, quality, and energy mix.

The results of LCA studies comparing textile end-of-life scenarios demonstrate the higher environmental benefits of reuse compared to current recycling options in the global market. The study comparison also demonstrates differences in CO_2 abatement for various fibre types for a given EOL scenario.

5.0 Industry Collaboration

It is becoming increasingly evident that a collaborative effort is required from industry stakeholders to advance end-of-life management strategies, facilitate better emissions inventory data for estimations and tracking over time. Cross-sector collaboration can address the complex and interconnected challenges associated with sustainable fashion, identify innovative solutions, share knowledge and resources, and facilitate a transition towards a circular economy for the textiles and apparel industry.

This section presents a non-exhaustive list of industry collaborations and organizations related to tracking and/or implementing EOL textile waste management solutions and strategies. This includes consortia, platforms, working groups, and organizations across Canada and worldwide.

Table 3. Industry collaborations and organizations whose work covers textile waste management/EOL solutions

Western Canada (British Columbia, Alberta)		
Alberta Circular Economies Initiatives with Recycling Council of Alberta	Circular Economies Initiative (Banff, Strathcona County, Lethbridge): implementation of economic models focused on reuse, sharing, recycling, upcycling and other sustainable practices to reduce waste and pollution.	https://www.apega.ca/about-apega/publications/yourpeg/alberta-communities-go-circular-for-the-environment https://www.strathcona.ca/your-property-utilities/garbage-and-recycling/recycling/textiles/
BC Apparel and Gear Association (BCAG)	Collective of Apparel and Gear brands and professionals in British Columbia. Supporting and growing industry talent, scaling growth, and sustainability goals in the industry	https://www.bcapparelandgear.com/
Indigenous Zero Waste Technical Advisory Group (IZWTAG)	Offers training and resources to First Nations to implement zero waste systems in communities. Resources and training offered on reuse, repair, recycling, composting, waste management and reduction activities.	https://izwtag.com/
Kootenay Outdoor Recreation Enterprise Initiative (KORE)	Organization dedicated to connecting and promoting craft gear creators, makers, innovators, designers in the outdoor manufacturing sector	https://koreoutdoors.org/
Sea to Sky Outdoor Adventure Recreation Enterprise Society (SOARE)	Potential future network supporting Sea-to-Sky region makers, entrepreneurs, educators, organizations in the outdoor industry. Goals to support sustainable practices and processes, foster innovation, local supply-chain development, and circular economy	https://pub-rmow.escribemeetings.com/filestream.ashx?DocumentId=17558
Textile Lab for Circularity (TLC)	Social Innovation Lab that facilitates cross-sector collaboration within the textiles industry on waste diversion and sustainability, education around circular business strategy	https://www.labforcircularity.com/
Waste Free Edmonton (WFE)	Organization working to reduce waste in Edmonton through awareness around producing and consuming less, reusing, repurposing items. Engages with government, business, organization, and citizens.	https://wastefree.ca/

Canada-Wide		
Fashion Takes Action	Non-profit organization working to advance sustainability in the fashion system through education, awareness, research, collaboration.	https://fashiontakesaction.com/
Canadian Circular Textile Consortium (CCTC)	An in-development consortium of value chain stakeholders comprising working groups engaged in projects related to the development of a circular textile economy for Canada.	Coming in Spring 2023 https://fashiontakesaction.com/circularity/
National Association of Charitable Textile Recyclers (NACTR)	Network of Canadian charities working to promote charitable textile reuse, recycling, thrift retail.	https://nactr.ca/
Waste Wiki – York University	Partnering as subject matter experts and resource partners in assisting organizations with waste diversion and tracking strategies.	https://wastewiki.info.yorku.ca/
National Zero Waste Council of Canada (Circular Economy, Reuse, Waste Prevention focus areas)	Council of cross-sector organizations to advance waste prevention and circular economy in Canada	http://www.nzwc.ca/focus-areas/
Worldwide		
American Circular Textiles (ACT) Policy Group	Multi-stakeholder initiative that works towards supportive policy for transitioning to a circular fashion economy, textile recovery and reuse solutions	https://www.americancirculartextiles.com/
Accelerating Circularity Project	Collaboration of organizations that work to catalyze new supply chains, business models for spent textiles to mainstream raw materials	https://www.acceleratingcircularity.org/
European Community of Practice for a Sustainable Textile Ecosystem (ECOSYSTEX)	Works to accelerate collaboration in the textile sustainability and circularity field. Comprises 17-EU funded member projects focused on textile sustainability.	https://textile-platform.eu/ecosystex
European Apparel and Textile Confederation (EURATEX) – Recycling Hubs (ReHubs) initiative	European initiative for industrial upcycling of textile waste streams and circular materials, scale-up of collecting, sorting, processing, recycling of pre- and post-consumer materials	https://www.rehubs.eu/
EuRIC Textiles – Textiles Re-use & Recycling Branch	Consortium of organizations and companies working to advance the collective interests of European textile recycling and reuse industries; evaluate and provide input on implementation of EU textiles strategy	https://euric-aisbl.eu/about/governance-structure/branches/euric-textiles
European Technology Platform for the Future of Textiles and Clothing (Textile ETP)	European open expert network of professionals involved in textile and clothing-related research and innovation.	https://textile-platform.eu/
Platform for Accelerating the Circular Economy (PACE) – Textile Action Agenda	Global collaboration platform for leaders in business, government, civil societies to share vison, best practices to scale circular economy for textiles	https://pacecircular.org/action-agenda/textiles
TEXAID	Consortium of organizations with network of collection, sorting, recycling options for used textiles in Europe	https://www.texaid.ch/en/about-texaid/about-texaid.html

Textile Recycling Excellence Project (T-REX)	Project that brings together 12 value chain stakeholders working to create a harmonized EU blueprint, business opportunities for scaling and implementing closed-loop sorting, recycling of household textile waste to usable feedstock.	https://trexproject.eu/
Zero Discharge of Hazardous Chemicals (ZDHC) Programme	Collaboration of brands, value chain affiliates, contributors to advancing zero discharge of hazardous chemicals in textile, leather, footwear industries.	https://www.roadmaptozero.com https://apparelcoalition.org/collaboration-impact-zdhc/

6.0 Conclusions & Outlook

This report has reviewed studies and methods employed for emissions modeling and provided an analysis of the comparative impacts of various textile waste management solutions. Studies reviewed consistently found higher GHG reduction benefits of reuse strategies compared to current recycling options in the global market. Potential approaches have been presented to compile data and estimate emissions specific to end-of-life textile waste management solutions based on industry standards and guidance. Global industry collaborations specific to implementing and advancing end-of-life management strategies have been summarized.

To better understand the impacts of textile waste reduction strategies, it is crucial to have accurate emissions modeling that can estimate the potential benefits of selected solutions. This information can greatly inform industry stakeholders, enabling them to plan and implement effective waste reduction measures, and identify the most impactful areas to focus on. A key enabling factor to advance the quality and consistency of data collection is engaging in collaborative efforts to collect primary inventory data for key processes and relevant supplier data for brands and retailers. Understanding the potential benefits of waste reduction strategies from a climate perspective will facilitate informed decision-making and actionable steps towards sustainable industry practices.

7.0 Recommendations & Next Steps

To advance the understanding of modeling environmental impacts of textile waste management solutions, the following recommendations and next steps are presented:

General

- Employ greater reuse/repurpose/repair strategies to facilitate the transition towards circular economy strategies
- Collaboration between stakeholders (manufacturers, retailers/brands, waste management organizations, policymakers) to develop effective strategies for textile waste management, emissions modeling, share relevant data and findings
- Increased education and opportunities to support improved EOL management practices among industry and consumers
- Provide more guidance to industry on accessing and conducting LCAs that incorporate end-of-life considerations

Enhance Data Collection

- Collect and organize data to perform emissions modeling for textile and apparel industry stakeholders in Canada (reuse/takeback programs, textile recycling plants, sorter/grader materials stream analysis)
- Digital solutions to streamline data collection among stakeholders
- Harmonize the textile & apparel categories that are assessed in municipal and regional waste audits
- Greater harmonization of emissions reporting tactics and publication to avoid duplication of efforts and enable comparisons across organizations and sector
- Western Canada/Canada-wide: Compile, isolate, track textile waste materials stream inventory data for environmental reporting and to enable future emissions modeling to be carried out

Future work: Potential Near-Term Applications for EOL Emission Modeling in Western Canada

During the research, the two processes which bore the highest potential to effectively model comparative EOL management include:

- Assessing the technology and process of General Recycled. This company has an existing process in Quebec, recycling and converting used flame-resistant (FR) aramids (e.g., industrial workwear) into recycled FR fabrics and garments
- Assessing the impact of existing diversion strategies from sorter/graders which deploy textile waste diversion/reverse logistics (e.g., Debrand Services Inc.) for specific stream analysis

References

[1] M. Sadowski, L. Perkins, and E. McGarvey, "Roadmap to Net Zero: Delivering Science-Based Targets in the Apparel Sector," 2021. doi: 10.46830/wriwp.20.00004.

[2] Ellen MacArthur Foundation, "A New Textiles Economy: Redesigning Fashion's Future," 2017. [Online]. Available: https://archive.ellenmacarthurfoundation.org/assets/downloads/A-New-Textiles-Economy.pdf

[3] S. Sharpe, E. Dominish, and M. C. Martinez Fernandez, "Taking climate action: measuring carbon emissions in the garment sector in Asia," ILO, 2022. doi: 10.54394/wawn5871.

[4] United States Environmental Protection Agency, "Textiles: Material-Specific Data," 2022. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/textiles-material-specific-data

[5] Cheminfo Services Inc., "Characterizing reuse, recycling and disposal of textiles in Canada," no. 905, 2022.

[6] B. Zamani, "Carbon footprint and energy use of textile recycling techniques," 2011. [Online]. Available: http://publications.lib.chalmers.se/records/fulltext/146872.pdf

[7] B. Zamani, M. Svanström, G. Peters, and T. Rydberg, "A Carbon Footprint of Textile Recycling: A Case Study in Sweden," *J. Ind. Ecol.*, vol. 19, no. 4, pp. 676–687, Aug. 2015, doi: 10.1111/JIEC.12208.

[8] G. Sandin and G. M. Peters, "Environmental impact of textile reuse and recycling – A review," *Journal of Cleaner Production*, vol. 184. Elsevier Ltd, pp. 353–365, May 20, 2018. doi: 10.1016/j.jclepro.2018.02.266.

[9] P. H. Brunner and H. Rechberger, "Handbook of Material Flow Analysis: For Environmental, Resource, and Waste Engineers, Second Edition," Dec. 2016, doi: 10.1201/9781315313450.

[10] V. Amicarelli and C. Bux, "Quantifying textile streams and recycling prospects in Europe by material flow analysis," 2022, doi: 10.1016/j.eiar.2022.106878.

[11] Y. Luo, K. Song, X. Ding, and X. Wu, "Environmental sustainability of textiles and apparel: A review of evaluation methods," *Environ. Impact Assess. Rev.*, vol. 86, no. May 2020, p. 106497, 2021, doi: 10.1016/j.eiar.2020.106497.

[12] A. Malakahmad, M. S. Abualqumboz, S. R. M. Kutty, and T. J. Abunama, "Assessment of carbon footprint emissions and environmental concerns of solid waste treatment and disposal techniques; case study of Malaysia," *Waste Manag.*, vol. 70, pp. 282–292, Dec. 2017, doi: 10.1016/J.WASMAN.2017.08.044.

[13] T. Karthik and R. Murugan, "Carbon footprint in denim manufacturing," *Sustain. Denim*, pp. 125–159, Jan. 2017, doi: 10.1016/B978-0-08-102043-2.00006-X.

[14] M. Z. Hauschild *et al.*, "Identifying best existing practice for characterization modeling in life cycle impact assessment," *Int. J. Life Cycle Assess.*, vol. 18, no. 3, pp. 683–697, Mar. 2013, doi: 10.1007/S11367-012-0489-5/METRICS.

[15] Water Footprint Network, "What is water footprint assessment?," 2022. https://www.waterfootprint.org/water-footprint-2/what-is-water-footprint-assessment/

[16] International Standards Organization, "ISO - ISO 14046:2014 - Environmental management — Water footprint — Principles, requirements and guidelines," 2014. [Online]. Available: https://www.iso.org/standard/43263.html

[17] M. Nordborg *et al.*, "Updated indicators of Swedish national human toxicity and ecotoxicity footprints using USEtox 2.01," *Environ. Impact Assess. Rev.*, vol. 62, pp. 110–114, Jan. 2017, doi: 10.1016/J.EIAR.2016.08.004.

[18] F. Soheilifard, A. Marzban, M. Ghaseminejad Raini, M. Taki, and R. van Zelm, "Chemical footprint of

pesticides used in citrus orchards based on canopy deposition and off-target losses," *Sci. Total Environ.*, vol. 732, p. 139118, Aug. 2020, doi: 10.1016/J.SCITOTENV.2020.139118.

[19] P. Fantke *et al.*, "Toward Harmonizing Ecotoxicity Characterization in Life Cycle Impact Assessment," *Environ. Toxicol. Chem.*, vol. 37, no. 12, p. 2955, Dec. 2018, doi: 10.1002/ETC.4261.

[20] N. Terinte, B. M. K. Manda, J. Taylor, K. C. Schuster, and M. K. Patel, "Environmental assessment of coloured fabrics and opportunities for value creation: spin-dyeing versus conventional dyeing of modal fabrics," *J. Clean. Prod.*, vol. 72, pp. 127–138, Jun. 2014, doi: 10.1016/J.JCLEPRO.2014.02.002.

[21] F. Qi, L. Qian, J. Liu, X. Li, L. Lu, and Q. Xu, "A high-throughput nanofibers mat-based micro-solid phase extraction for the determination of cationic dyes in wastewater," *J. Chromatogr. A*, vol. 1460, pp. 24–32, Aug. 2016, doi: 10.1016/J.CHROMA.2016.07.020.

[22] World Business Council for Sustainable Development; and Five Winds International;, "Eco-efficiency Learning Module," 2006.

[23] K. J. Watson and S. G. Wiedemann, "Review of Methodological Choices in LCA-Based Textile and Apparel Rating Tools: Key Issues and Recommendations Relating to Assessment of Fabrics Made From Natural Fibre Types," *Sustain. 2019, Vol. 11, Page 3846*, vol. 11, no. 14, p. 3846, Jul. 2019, doi: 10.3390/SU11143846.

[24] Sustainable Apparel Coalition, "Higg Product Tools." https://apparelcoalition.org/higg-product-tools/ (accessed Mar. 26, 2023).

[25] F. Briten, "Fashion brands pause use of sustainability index tool over greenwashing claims," *The Guardian*, 2022. https://www.theguardian.com/fashion/2022/jun/28/fashion-brands-pause-use-of-sustainability-index-tool-over-greenwashing-claims (accessed Mar. 18, 2023).

[26] J. M. Chua, "H&M Greenwash Warning Fuels 'Urgent' Higg MSI Review – Sourcing Journal," *Sourcing Journal*, 2022. https://sourcingjournal.com/sustainability/sustainability-news/higg-material-sustainability-index-sustainable-apparel-coalition-norway-hm-norrona-350831/ (accessed Mar. 18, 2023).

[27] R. Deeley, "Dutch, Norwegian Regulators Issue Guidance on Controversial Higg Tool | BoF," *The Buisness of Fashion*, 2022. https://www.businessoffashion.com/news/sustainability/dutch-norwegian-regulators-issue-guidance-on-controversial-higg-tool/ (accessed Mar. 18, 2023).

[28] A. Razvi, "Statement from the SAC Regarding the Norwegian Consumer Authority and Environmental Claims," *Sustainable Apparel Coalition*, 2022. https://apparelcoalition.org/blog/statement-from-the-sac-regarding-the-norwegian-consumer-authority-and-environmental-claims/ (accessed Mar. 18, 2023).

[29] World Business Council for Sustainable Development; and W. R. Institute;, "A Corporate Accounting and Reporting Standard," 2012.

[30] World Business Council for Sustainable Development; and World Resources Institute;, "Corporate Value Chain (Scope 3) Accounting and Reporting Standard, Supplement to the GHG Protocol Corporate Accounting and Reporting Standard," 2011.

[31] World Business Council for Sustainable Development; and World Resources Institute;, "Product Life Cycle Accounting and Reporting Standard," 2011, [Online]. Available: http://www.ghgprotocol.org/files/ghgp/public/Product-Life-Cycle-Accounting-Reporting-Standard-EReader_041613.pdf

[32] European Commission, "Environmental footprint methods." https://green-business.ec.europa.eu/environmental-footprint-methods_en

[33] European Commission, "PEFCR Guidance document - Guidance for Product Environmental Footprint Category Rules (PEFCRs)," *PEFCR Guid. Doc.*, p. 238, 2018.

[34] European Commission, "Understanding Product Environmental Footprint and Organisation Environmental Footprint methods," 2021. [Online]. Available: https://ec.europa.eu/environment/eussd/smgp/pdf/EF simple guide_v7_clen.pdf

[35] S. Bamonti, R. Spinelli, and A. Bonoli, "Environmental footprint in the production of recycled wool," *Environ. Eng. Manag. J.*, vol. 15, no. 9, pp. 1923–1931, 2016, doi: 10.30638/EEMJ.2016.207.

[36] V. Bach, A. Lehmann, M. Görmer, and M. Finkbeiner, "Product Environmental Footprint (PEF) Pilot Phase—Comparability over Flexibility?," *Sustain. 2018, Vol. 10, Page 2898*, vol. 10, no. 8, p. 2898, Aug. 2018, doi: 10.3390/SU10082898.

[37] "Environmental Footprint methods." https://green-business.ec.europa.eu/environmental-footprint-methods_en

[38] "Primary vs. secondary data - What's the best in LCA? - Ecochain - LCA software company." https://ecochain.com/knowledge/primary-vs-secondary-data-in-lca/

[39] L. A. Espinoza Pérez, A. T. Espinoza Pérez, and Ó. C. Vásquez, "Exploring an alternative to the Chilean textile waste: A carbon footprint assessment of a textile recycling process," *Sci. Total Environ.*, vol. 830, p. 154542, Jul. 2022, doi: 10.1016/J.SCITOTENV.2022.154542.

[40] T. Semba, Y. Sakai, M. Ishikawa, and A. Inaba, "Greenhouse Gas Emission Reductions by Reusing and Recycling Used Clothing in Japan," *Sustain. 2020, Vol. 12, Page 8214*, vol. 12, no. 19, p. 8214, Oct. 2020, doi: 10.3390/SU12198214.

[41] A. Koligkioni, K. Parajuly, B. L. Sørensen, and C. Cimpan, "Environmental Assessment of End-of-Life Textiles in Denmark," *Procedia CIRP*, vol. 69, pp. 962–967, Jan. 2018, doi: 10.1016/J.PROCIR.2017.11.090.

[42] S. Trzepacz, N. Dina Bekkevold Lingås, N. Lise Asscherickx, V. Karolien Peeters, V. Hilde van Duijn, and E. Marieke Akerboom, "LCA-based assessment of the management of European used textiles," 2023.

[43] Prada S.p.A;, "PRADA Group, Sustainability Report," 2021. [Online]. Available: https://www.pradagroup.com/content/dam/pradagroup/documents/Responsabilita_sociale/2022/e-Sustainability Report 2021.pdf

[44] NIKE Inc., "FY21 NIKE, Inc. Impact Report," 2021. [Online]. Available: https://purpose-cms-preprod01.s3.amazonaws.com/wp-content/uploads/2022/03/17210319/FY21_NIKE-Impact-Report.pdfpr

Appendices

A1 - Emissions estimation/modeling methods used for analyzing textile end-of-life scenarios

Method	Software/Databases/Standards	Types of Reported Data (Units)	Process Examples
Lifecycle Assessment (LCA)	Software (various): openLCA, SimaPro, GaBi, Ecochain, EASETECH (enviro assessment of solid waste systems and technology), SULCA Databases: GaBi, EcoInvent, US Life Cycle Inventory Database (USLCI), European Reference Life Cycle Database (ELCD); databases created specifically for certain industries / or research publications, independent data from facilities, pilot processes ISO 14040:2006 series (14040, 14044; Principles and framework, and Requirements and guidelines, respectively)	Global warming potential, primary energy savings, GHG equivalent savings -mass of CO_2eq - GJ (energy consumption/savings)	Cradle-to-gate scenarios examining impact of recycling (mechanical or chemical), mixed waste recycling, remanufacturing for reuse, landfilling, incineration with energy recovery. Covered in report.
Environmental Footprint	Databases: USEtox® 2.0 characterization factors in LCA software; EU Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) eco-toxicology data -British Standards Institute, BS PAS 2395:2014 Specification for the assessment of greenhouse gas emissions from the whole life cycle of textile products à general methodologies for GHG emissions assessments applied to textile products; supplements PAS 2050 Carbon Footprinting – A life cycle GHG emissions of goods and services (not textile specific) -ISO14046:2014 environmental management -water footprint – principles, requirements, and guidelines (LCA derived) Data from research papers, enterprises/manufacturing facilities, pilot scale processes, primary process data	Carbon footprint: amount of CO_2 or CO_2 eq emitted directly or indirectly over life of an activity, product, service, or geographical area; [mass]CO_2/[mass] fibres; [mass]CO_2eq / [mass] fibre Water footprint: impact caused by water resources consumption, and pollutant discharges [mass or volume]H_2Oeq/[mass] fibres	-Carbon footprint and water footprint assessment of virgin and recycled PET textiles by examining key semi-product manufacturing processes[1] -carbon footprint, water use, water scarcity footprint of cellulose carbamate fibre production using discarded cotton textiles as raw material; comparison of results from virgin cotton and viscose fibre production[2]

[1] W. Qian, X. Ji, P. Xu, and L. Wang, "Carbon footprint and water footprint assessment of virgin and recycled polyester textiles," https://doi.org/10.1177/00405175211006213, vol. 91, no. 21–22, pp. 2468–2475, Apr. 2021, doi: 10.1177/00405175211006213.

[2] S. Paunonen, T. Kamppuri, L. Katajainen, C. Hohenthal, P. Heikkilä, and A. Harlin, "Environmental impact of cellulose carbamate fibers from chemically recycled cotton," J. Clean. Prod., vol. 222, pp. 871–881, Jun. 2019, doi: 10.1016/J.JCLEPRO.2019.03.063.

Method	Software/Databases/Standards	Types of Reported Data (Units)	Process Examples
Material Flow Analysis (MFA)	Software: STAN 2.6 (subSTance flow ANalysis) from Institute for Water Quality, Resources and Waste Management at Vienna University of Technology; OMAT (online material flow analysis tool, free) Data from research papers, primary process data	Mass balance (material weight) as functional input units, from processes specified for analysis, calculation of CO_2eq emission (t) flows, Energy consumption (GJ)	-Estimation of textile waste, energy, CO_{2eq}. emissions streams in Europe based on various EOL scenarios [3]
Higg Index	Higg Modules (product, facility, or brand & retail) Product Module covers use and EOL in value chain. LCA data can be obtained from Higg Materials Sustainability Index (MSI), Higg Product Module (PM), related data collected from brand partners	-Scoring system out of 100 (higher = better enviro performance) -Score based on product/manufacturing related questions; some predetermined standard values based on global survey for materials used in score determination	-Evaluation of environmental sustainability (materials and manufacturing) of knitted t-shirts [4] -Evaluation of environmental performance of uniform production facility to identify areas for improvement in manufacturing phase [5]
Eco-Efficiency	Data from research papers, company/facility interviews Environmental impact portion may use LCA methods and software for analysis	-Eco-cost (input from LCA impact calculated in kg impact eq; output in impact prevention costs) -Net value = selling $ – prod $ -Eco-efficiency index (EEI) = (price-cost)/(cost+eco cost) -Eco-cost per value (EVR) = (eco cost)/(net value) -Eco-efficiency rate (EER) = (1-EVR)x100% -Economic gains ($), mass intensity total total (sum of biotic compartments, abiotic, air, water for a given process)	-assessment of eco-efficiency of recovery of cellulose from textile waste shredding [6] -various eco-efficiency indices calculated for weaving factory comparison; gate-to-gate LCA for material and production activity, economic data from interviews, literature; calculation of eco-cost based impact generated from LCA [7]

[3] V. Amicarelli and C. Bux, "Quantifying textile streams and recycling prospects in Europe by material flow analysis," 2022, doi: 10.1016/j.eiar.2022.106878.

[4] M. Mashiur, R. Khan, and M. Islam, "Materials and manufacturing environmental sustainability evaluation of apparel product: knitted T-shirt case study," 2011, doi: 10.1186/s40689-015-0008-8.

[5] H. Cao, M. A. Dickson, K. Cobb, M. Carper, C. Scudder, and C. Wong, "Applying a sustainability performance measurement tool in designing and developing automotive employee uniforms," http://dx.doi.org/10.1080/17543266.2014.992051, vol. 8, no. 2, pp. 78–86, May 2014, doi: 10.1080/17543266.2014.992051.

[6] G. C. de O. Neto, M. M. Teixeira, G. L. V. Souza, V. D. Arns, H. N. P. Tucci, and M. Amorim, "Assessment of the Eco-Efficiency of the Circular Economy in the Recovery of Cellulose from the Shredding of Textile Waste," Polym. 2022, Vol. 14, Page 1317, vol. 14, no. 7, p. 1317, Mar. 2022, doi: 10.3390/POLYM14071317.

[7] Y. Y. Siagian, R. Sinaga, C. Sinaga, and Y. Manik, "Life cycle assessment and eco-efficiency Indicator for ulos weaving using loom machine in Toba Samosir Regency of North Sumatra", doi: 10.1051/e3sconf/20187405002.

Method	Software/Databases/Standards	Types of Reported Data (Units)	Process Examples
GHG Protocol Initiative	Corporate Standard Scope 3 Standard Product Standard Builds on frameworks and requirements from ISO LCA standards 14040:2006, Life Cycle Assessment: Principles and Framework and 14044:2006, Life Cycle Assessment: Requirements and Guideline; BASI/DEFRA PAS 2050 – Assessment of Lifecycle Greenhouse Gas Emissions of Goods and Services, ILCD (International Reference Life Cycle Data System) Handbook	-All emissions converted and reported in mass of CO_2e	Calculation guidance for relevant Scope 3 categories covered in report.
Product Environmental Footprint – Category Rules (PEFCR): Apparel and Footwear	EU, UK PEFCR for apparel and footwear, 2021 (in draft version) Adapted from some frameworks and requirements from ISO LCA standards 14040:2006, Life Cycle Assessment: Principles and Framework and 14044:2006, ISO 14021:2016 Environmental labels and declarations	-Follows some LCA analysis methods, functional units need to be defined, other units specified based on calculations being carried out	Relevant calculation guidance provided in PEFCR: Apparel & Footwear (draft) Examples: -Quality loss from use of recycled yarns in clothing and footwear materials (PEFCR draft) -Environmental footprint in production of recycled wool; use of LCA and protocol to analyze inventory data quality specified by PEF

A2 - Resource Links

- Product Standard - GHG Protocol, World Resources Institute and World Business Council for Sustainable Development, 2011 link
- Corporate Standard - GHG Protocol, World Resources Institute and World Business Council for Sustainable Development, 2011 link
- Scope 3 Calculation Guidance, v1.0, GHG Protocol, World Resources Institute and World Business Council for Sustainable Development, 2013 link
- Scope 1 and Scope 2 Inventory Guidance, US EPA, 2022 link
- Scope 3 Inventory Guidance, US EPA, 2023 link
- Apparel and Footwear Science-Based Targets Guidance, World Resources Institute (WRI) on behalf of the Science Based Targets initiative (SBTi), 2019 link
- Global Warming Potential Values, GHG Protocol, 2016 link
- Global Warming Potentials, Government of Canada, 2023 link
- Emission Factor Database, Intergovernmental Panel on Climate Change (IPCC), 2021 link
- ISO 14064-1:2018 Greenhouse gasses — Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals link
- Canadian Environmental Sustainability Indicators: Greenhouse gas emissions, Environment and Climate Change Canada, 2022 link