Examining Cut-and-Sew Textile Waste within the Apparel Supply Chain

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Acronym Glossary

AEP	aquatic eutrophication potential
ALO	agricultural land occupation
AP	acidification potential
CH_4	methane
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CSRD	Corporate Sustainability Reporting Directive
DPP	digital product passport
EPR	extended producer responsibility
ESPR	European Sustainable Products Regulation
EU	European Union
FU	functional unit
GHG	greenhouse gas
GWh	gigawatt hours
GWP	global warming potential
Higg FEM	Higg Facility Environmental Module
IL	ionic liquids
IPCC	Intergovernmental Panel on Climate Change
kg	kilogram
kWh	kilowatt hours
LCIA	life cycle impact assessment
LCA	life cycle assessment
MESM	Masters of Environmental Science and Management
MMCF	man-made cellulosic fiber

MONRE	Ministry of Natural Resources and Environment
MSW	municipal solid waste
N eq.	Nitrogen equivalent
NGO	non-governmental organization
NMMO	N-methylmorpholine oxide
NMVOC	non-methane volatile organic compounds
NO_x	Nitrous oxides
O_3 eq.	ozone equivalent
PAH	polycyclic aromatic hydrocarbon
PCDD	polychlorinated dibenzo-p-dioxins
PCDF	polychlorinated dibenzofurans
PET	polyethylene terephthalate
PLM	product line management
PM	particulate matter
SDS	safety data sheet
SO_2e	sulfur dioxide equivalent
TEP	Terrestrial Eutrophication Potential
UCSB	University of California, Santa Barbara
USD	United States dollar
UV	ultraviolet
WTE	waste-to-energy

Objectives

Apparel manufacturing facilities produce pre-consumer waste in the fabric cut-and-sew process. This project aimed to analyze the impact of pre-consumer textile waste in the cut-and-sew process for Patagonia, the outdoor apparel retailer. This was accomplished through the following objectives:

1. Quantify the amounts of pre-consumer cotton, nylon, and polyester waste generated in Tier 1 facilities within Patagonia's Vietnamese supply chain.

2. Determine the environmental and public health impacts associated with textile landfilling, incinerating, mechanical recycling, and chemical recycling.

3. Provide a waste management and stakeholder engagement recommendation that minimizes impacts based on Vietnam's existing infrastructure, environmental policy, regional challenges, and opportunities.

Significance

A Hidden Sustainability Problem

Textile waste is divided into two categories: pre- and post-consumer. Post-consumer waste refers to garments disposed of after consumer use. Pre-consumer waste, also referred to as industrial waste, describes waste generated during the manufacturing process. This project focused on fabric waste generated during the cut-and-sew process in manufacturing facilities. Fabric is cut into predetermined shapes based on a sewing pattern and sewn into a garment. The unused fabric is known as cut-and-sew or scrap waste.

Due to social media and extended producer responsibility (EPR) pressure, many brands are addressing post-consumer apparel waste. However, pre-consumer textile waste produced in cut-and-sew factories remains a relatively hidden problem. After reviewing 40 apparel company websites, the team found no public disclosure of the volume or weight of pre-consumer waste created in the cut-and-sew process.

Cut-and-sew waste remains unseen for many reasons. The most significant factor is the structure of the apparel industry's supply chain. Apparel brands do not own their production facilities; instead, brands contract with independent garment factories to sew their garments (Paton & Maheshwari, 2019). Garment factories typically specialize in one garment type (e.g. outerwear), and manufacture that garment for several brands in one facility (Synerg, 2023). Brands place garment orders to factories and pay for the finished pieces. Brands pay the price of the finished garment, not for the fabric it is sewn from. If brands were directly responsible for the cost of fabric, they would have a financial incentive to track and minimize the waste. The dispersed nature of the apparel supply chain means pre-consumer waste is not a line item on brand's manufacturing invoices.

The Importance of Pre-Consumer Textile Waste

Despite their value, large volumes of fabric are discarded annually. Bangladesh's apparel industry generated approximately 577,000 tonnes of waste in 2019, of which almost half was 100% recyclable cotton, with an approximate value of $100 million USD (Pavarini, 2021). FabScrap, a non-profit fabric upcycler, stated, "For every pound of clothing fabric we throw away as a consumer, a business throws away 40 pounds" (Jones & Xu, 2021). Older estimates show that 10–15% of fabric is discarded in the cut-and-sew process (Rissanen, 2005). However, the team interviewed industry experts who shared that the percentage is likely higher. Even with an estimate of 10–15%, the magnitude of waste is considerable. Global fiber production reached a record 116 million tonnes in 2022 (Textile Exchange, 2023). If all fiber production that year was used to manufacture garments, 11.6–17.4 million tonnes would be wasted in the cut-and-sew process.

Quantifying the resources needed for fabric production is essential to understand the consequences of disposing of pre-consumer textiles. The environmental inputs of fabric production include energy from fossil fuels, chemicals, water, and land for natural fiber growth. The apparel industry alone accounts for an estimated 4–6.7% of global greenhouse gas (GHG) emissions (McKinsey & GFA, 2020; Quantis, 2018). If apparel production continues business-as-usual, it is estimated to account for 26% of the world's 2° carbon budget by 2050 (Ellen MacArthur Foundation, 2017). Understanding the resource-intensive stages in the apparel life cycle is crucial to minimize environmental impacts. Life Cycle Assessment (LCA) is used to parse environmental impacts by the product's life cycle stage: raw material extraction, production, transportation and distribution, use, and disposal. If the use phase is excluded from an apparel LCA, 91% of GHG emissions come from production, including fiber production, yarn preparation, fabric preparation, dyeing, and material finishing (Quantis, 2018). This is one tool the team employed to analyze the impact of disposal methods throughout this project.

Emerging Solutions for Pre-Consumer Textile Waste

Approximately 91% of a garment's life cycle GHG emissions come from the production phase, making it significant that an estimated 15% of that fabric is likely getting landfilled or incinerated before the material is turned into product (Quantis, 2018; Rissanen, 2005). There are emerging and developing opportunities to recycle this scrap waste to avoid the fate of landfill or incinerator. Pre-consumer textile waste has a higher potential for recycling than post-consumer textile waste since it is not contaminated by consumer use.

One effective way to reduce cut-and-sew waste is by making adjustments to sewing patterns and creating efficient marker plans. Sewing patterns are guides used to cut fabric to sew into garments and marker plans show how pattern cut-outs are configured on fabric. Marker plans can determine the amount of fabric waste produced by moving patterns around. While it is possible to design patterns that avoid waste, these low or zero-waste patterns restrict apparel design (Townsend & Mills, 2013). Low-waste patterns have a more blocky design, which may decrease the fit of clothing. Most people prefer clothes designed to fit the curves of the human body. Industry experts interviewed for the project shared that fabric-cutting efficiency is nearly maximized. Fabric-cutting efficiency measures the amount of fabric used in garments compared to the total fabric used in the process. After reviewing 50 apparel brands, only one company has publicly disclosed their fabric-cutting efficiency data. *686 Technical Apparel* discloses fabric-cutting efficiency of 87% (686 Technical Apparel, n.d.). This utilization rate means that if they used one square meter of fabric to make a garment, 13% of material was not used in the final garment. Due to fabric-cutting efficiency being nearly maximized in the industry, this project focused on end-of-life solutions for cut-and-sew scraps produced in apparel manufacturing facilities.

Client

Patagonia is an outdoor clothing retailer headquartered in Ventura, California, with a global supply chain. Currently, Patagonia works to minimize waste in the design and production of its products. According to their 2021 fiscal report, they focus on designing and fabricating the highest quality products, using repairable or recyclable materials, and partnering with customers to take mutual responsibility in minimizing the impact of the use and end-of-life stages through repair, reuse, and recycling. Patagonia has set a goal to only use preferred materials—organic and Regenerative Organic cotton, recycled polyester, and recycled nylon—by 2025. Using synthetic and natural fibers made from pre- and post-consumer waste, they aim to limit dependence on raw materials and reduce carbon emissions (Patagonia, 2024). For example, their use of recycled nylon fabrics in 2023 reduced carbon dioxide (CO_2) emissions more than 6.6 million pounds when compared to virgin nylon (Patagonia, 2024). Patagonia is interested in measuring not only GHG emissions reductions, but also other environmental and public health impacts.

Patagonia's supply chain involves factories and mills in 17 countries, with 14 located in the Global South. The Global South refers to low-income and marginalized Latin America, Asia, Africa, and Oceania countries. While operating in the Global South, Patagonia engages in various due diligence activities to promote and sustain fair labor practices, safe working conditions, and environmental responsibility for the finished-goods factories, farms, and mills. With this project, Patagonia aimed to address the impacts of waste and recycled products beyond the factories. By better understanding these effects, they can work to reduce their negative impacts in local communities and promote these efforts across the industry.

Audience

This project aimed to bring attention to pre-consumer textile waste and to inspire brands to measure this waste in their supply chain. This project's broader audience includes other apparel brands, industry groups, and academic institutions. Brands have the power to measure impacts, bring awareness to pre-consumer textile waste, and adopt textile recycling solutions. Additionally, brands can use this report to assess end-of-life options for textile waste while considering the regional context and community impacts. Non-governmental organizations (NGOs) can utilize this report to advocate for solutions to the industry's collective impacts. Academic institutions can use this project's methods to conduct end-of-life pre-consumer textile impact research. LCA commissioners can use the findings of this project to advocate for including and improving end-of-life impacts in their analyses. By highlighting the impacts of pre-consumer textile waste, this report intends to support these stakeholders with improving supply chain traceability and supporting the development of a circular economy.

Background

Materials

This project focuses on the disposal of pre-consumer cotton, polyester, and nylon waste. These three materials comprise approximately 80% of the global fiber market (Textile Exchange, 2021). Cotton is the most widely used natural textile fiber, encompassing around one-fourth of the global fiber market (Textile Exchange, 2021). Virgin cotton fiber production is notorious for its high water and chemical demand, which makes recycled cotton or cotton alternatives highly environmentally desirable (Palme, 2017). Polyester, a synthetic fiber made from purified terephthalic acid and ethylene glycol, accounted for more than half of the global fiber market in 2020, totaling an estimated 109 million tons (Textile Exchange, 2021). Polyester production has exponentially increased since the 1970s to keep up with the growing population and associated textile demand. Nylon, or polyamide-based material, is the second-most common synthetic fiber but only encompasses around five percent of the global market share (Textile Exchange, 2021). The material is desired for its elasticity and resistance to wrinkling.

Textile Waste Management

This report will outline four management methods for disposal or reuse of pre-consumer textile waste: landfill, incineration, mechanical recycling, and chemical recycling. Each mode of disposal can be further categorized depending on its processes and technology.

Landfill

Modern landfills, also known as sanitary landfills, are classified based on the types of waste they accommodate, including industrial, hazardous, or municipal solid waste. A sanitary landfill is designed to prevent waste from contaminating the environment by using a protective barrier that separates the waste from groundwater and soil. Each day, incoming waste is spread in layers, compacted to reduce volume, and covered with soil. In order to be considered a sanitary landfill, landfill leachate must be collected and treated to avoid contamination with the surrounding environment. Sanitary landfills must be engineered to mitigate impacts to groundwater and surrounding water sources (Thurgood, 1999). Additionally, trained staff must be present to supervise onsite operations. Sanitary landfills are expensive to build and maintain, costing between $1.1 million–$1.7 million USD to construct and operate (U.S. EPA, 2014).

In contrast, unsanitary landfills or open dumpsites occur when waste is discarded directly onto land, such as roadsides, creek beds, or ditches. Since there is no barrier between the waste and the environment, there is an increased risk of environmental contamination (Al-Wabel et al., 2022). Approximately 40% of the world's waste ends up in open dumpsites, particularly in cities in middle and lower-income countries where economic constraints inhibit investment in waste management infrastructure (U. N. Environment, 2024). Individuals working at these sites and surrounding communities face high health risks and environmental pollution (U. N. Environment, 2024).

Landfills, including open dumpsites, represent around 10% of global anthropogenic GHG emissions due to the release of methane and carbon dioxide (Wang et al., 2023). Methane is a highly potent GHG that is released from the breakdown of organic material under anaerobic conditions (Wang et al., 2023). Managing methane emissions from landfills is a challenge because methane capture requires expensive gas collection systems (EPA, 2024). In order to capture methane emissions, landfills must be equipped with underground pipes, collection wells, and systems to collect methane for energy generation (EPA, 2024). Landfill methane capture can only achieve up to 85% percent efficiency in closed and engineered landfills, while in open dump sites, only around 10% of methane can be captured (Project Drawdown, 2023). The diagram below illustrates the main factors contributing to landfill methane emissions in a sanitary landfill, including the organic waste that produces methane and the inefficiencies in methane capture systems that result in methane leakage (Figure 1).

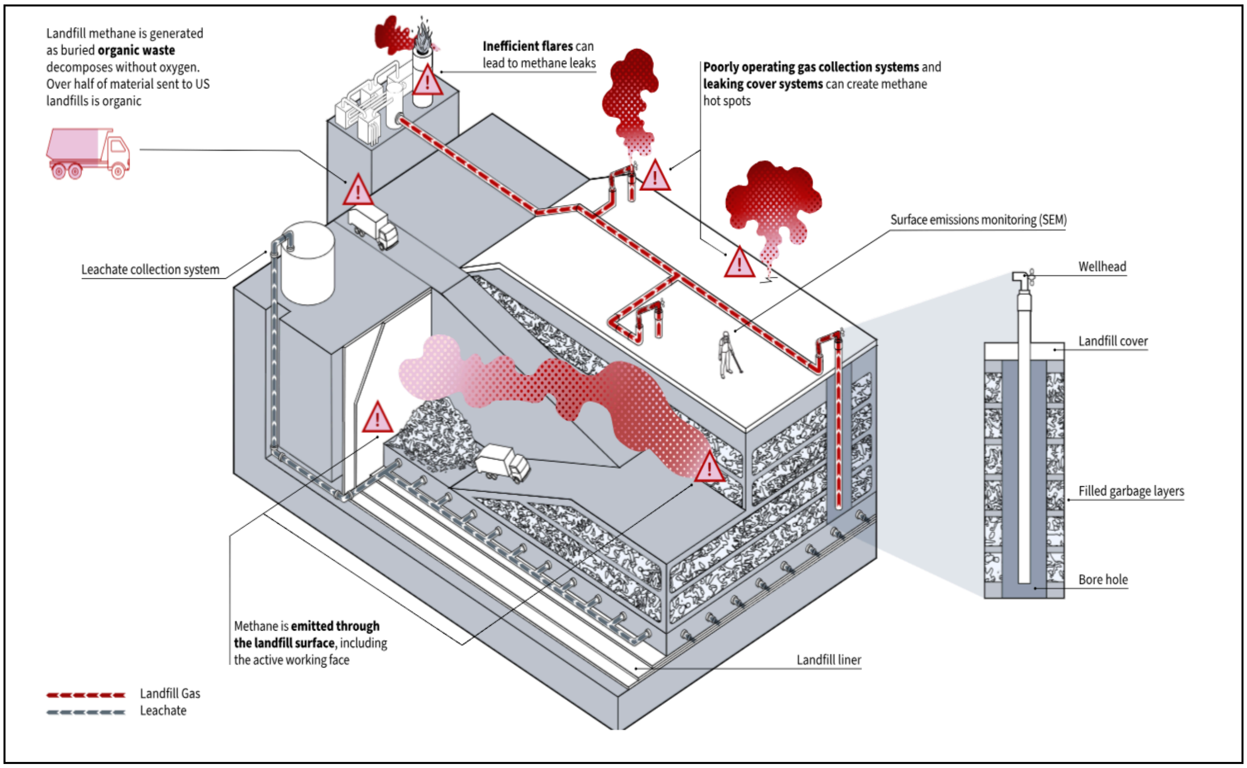

Figure 1 *Illustration of a sanitary landfill with methane emissions* (RMI, 2023)

Textile Degradation in Landfills

Decomposition in landfills involves both aerobic and anaerobic environmental conditions. Aerobic conditions are commonly found in open dump sites when the waste is not compacted or covered (Siddiqua et al., 2022). Anaerobic environments occur when waste materials are compacted and covered with soil. Anaerobic conditions cause very slow decomposition of material (ASTM International, 2020). Natural fibers like cotton will eventually biodegrade, but synthetic fibers like polyester and nylon will degrade into smaller particles.

Incineration

Incineration is the combustion of solid waste and can reduce waste volume by up to 90% (Tammemagi, 2000). Incineration facilities can be classified based on the type of waste they process and their technological capabilities. There are three types of incineration facilities: incineration without emission control, incineration with emission control, and waste-to-energy incineration. Typically, a facility specializes in one category of waste: municipal solid waste (MSW), hazardous, or medical. All incineration facilities with modern furnaces optimize combustion through technology such as grate systems to agitate waste, air injection systems, controlled gas flow, recirculation systems, and temperature maintenance.

Incineration facilities with emission controls require advanced technology, which increases construction, maintenance, and operational costs. One incineration facility can require a capital investment of between \$20 million–\$80 million USD (Xin-gang et al., 2016). This cost has increased along with stringent technical requirements for pollution and emissions control. Facilities employ many control techniques, including air pollution control devices, acid gas scrubbers, particulate collectors, and controls for nitrous oxide (NO_x), dioxin, and mercury removal (US NRC, 2000). Older or out-of-date incineration facilities are still in operation worldwide. Without proper emission control technology, these plants threaten the health of surrounding communities and the environment.

Waste-to-energy (WTE) incineration facilities are equipped with technology that enables power generation through a steam turbine (Figure 2). Through energy recovery, these facilities can reduce emissions relative to other incineration facilities. In the United States, a typical WTE plant generates 550 kilowatt hours (kWh) of energy per ton of combusted waste (US EPA, 2016). The potential energy generated is dependent on the calorific value of the material. For example, polyester has a higher potential for energy recovery than cotton (ScienceDirect Topics, n.d.). An average of 15–47% of energy used in textile production can be recovered through WTE incineration (Muthu, 2020). In summary, WTE can reduce overall emissions when compared to incinerators without energy recovery, but the efficiency depends on the type of waste being processed.

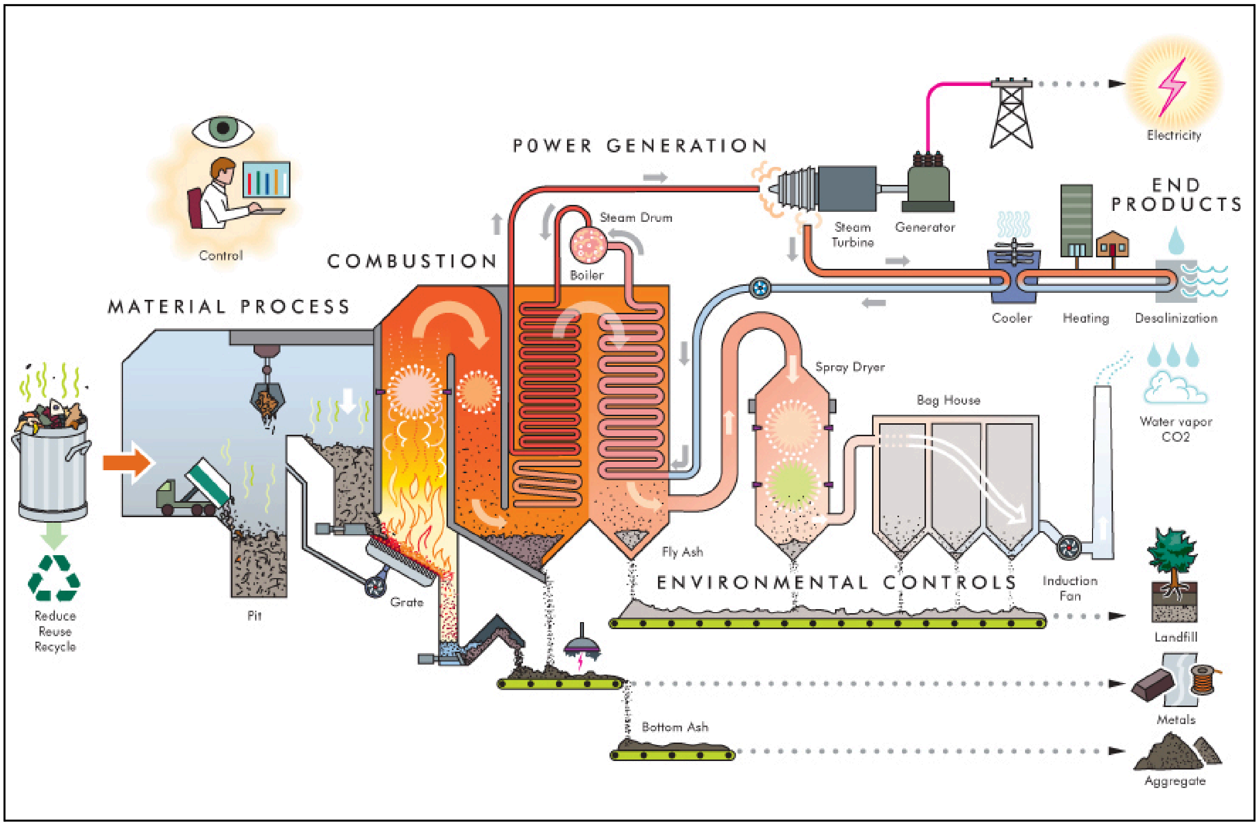

Figure 2 *Illustration of a modern waste-to-energy (WTE) incineration plant* (DeltaWay Energy, 2018)

Recycling

There are two main methods of textile recycling: mechanical and chemical. Mechanical recycling refers to physically altering the fiber format, while chemical recycling involves dissolving or depolymerizing the fibers with solvents. For pre-consumer textile waste to be recycled, the facility must have technology suitable for separating, sorting, and managing various textile materials. For example, components must be characterized and separated, including trim, buttons, zippers, and threads. The situation is further complicated with blended and synthetic fabrics because the amount and fibrous composition of the scrap fabric must be characterized and sorted. The recycling process should also cost the same or less than other modes of disposal. For textile waste to be recycled into another material, it must meet a minimum quality standard. If the waste is too degraded, it cannot be recycled and will be disposed of through landfill or incineration (Dobilaite et al., 2017; Le, 2018).

Mechanical Recycling

Mechanical recycling breaks down fiber structures into small pieces that can be re-spun or re-extruded into new fiber. This breakdown is usually done through shredding or grinding. However, it has some drawbacks. The sorting process is complicated, and the recycled fiber may not perform as well as the original. This is because the breakdown shortens the fiber's length, resulting in lower quality and weaker fabric.

Although there are distinct properties between natural and synthetic textiles, both undergo the same process during mechanical recycling. The materials are sorted based on composition, color, and blend content, cleaned to remove foreign materials and contaminants, and reduced in size through a crushing, grinding, shredding, or pulling mechanism. Natural fibers, like cotton, are then carded and respun into new fiber (Le, 2018). Synthetic fibers, like polyester and nylon, undergo a melting process to be re-extruded into a new product (Le, 2018). Once the fibers have been processed, they can be weaved or knit into a new fabric.

With natural fibers, blending the recycled fabric with virgin or synthetic materials is often necessary to maintain structural integrity. This combats the filament's lower tensile strength and softness from the filament shredding natural fibers (Johnson et al., 2020). Similarly, high-temperature exposure, ultraviolet (UV) radiation, and oxidation reduce recycled synthetic fiber quality. These factors cause a reduction in the polymer length chain and overall performance (Aguado et al., 1999). The recycling process is further complicated with dyes, contaminants, and other compounds. When polyester or nylon is mixed with other synthetics, any remaining contaminant materials can drastically decrease the quality of the final product. Nylon, specifically, has a lower melting point than other synthetics. This makes it susceptible to contamination and mandates a secondary cleaning process (Muthu et al., 2012). While mechanical recycling offers a more sustainable solution to textile disposal, the reduced fiber quality and risk of contamination prevent it from being widely adopted.

Chemical Recycling

Chemical recycling involves dissolving existing materials or polymers into chemical components or monomers for new applications (Textile Exchange, 2021). Two main chemical recycling processes are depolymerization and polymer dissolution. Depolymerization uses various chemicals, solvents, and heat to break down polymers into monomers and is primarily used for synthetic materials (Cefic, n.d.). Polymer dissolution is a process where the material is dissolved using solvents, separated to remove contaminants, and isolated by precipitating the polymer using an antisolvent to extract polymers and is primarily used for cotton and blended fabrics (Kol et al., 2022).

Many different chemicals and solvents are used in depolymerization. For this project, the team explored the impacts of the chemicals used in the main depolymerization processes: hydrolysis (acid, alkaline, and neutral), glycolysis, methanolysis, aminolysis, and ammonolysis (see Table 1; Bengtsson et al., 2022). These methods are currently being studied or commercially used to recycle polyester and nylon chemically.

Table 1 *Overview of depolymerization processes to chemically recycle polyester and nylon (Ghosal & Nayak, 2022; Paszun & Spychaj, 1997)*

Depolymerization Process		Description	Chemicals Used
Hydrolysis	Acid	Polyethylene terephthalate (PET) reacts with water molecules under acidic conditions at a high temperature (200–300°C) and pressure	hydrochloric acid, sulfuric acid, trifluoroacetic acid, formic acid, nitric acid
	Alkaline	PET reacts with water molecules under alkaline conditions at a high temperature and pressure	hydrochloric acid, potassium hydroxide, sulfuric acid, sodium hydroxide,
	Neutral	PET reacts with water molecules under neutral conditions at a high temperature (210–250°C) and pressure	terephthalic acid
Glycolysis		Transesterification reaction of PET with an excess of glycol; temperature range of 180–240°C	zinc acetate, sodium glycolate, poly(phosphoric acid), ethylene glycol,
Methanolysis		PET is degraded by methanol at a high temperature (160–200°C) and pressure	zinc acetate, methanol, magnesium acetate, cobalt acetate, lead oxide
Aminolysis		PET fibers or powder are degraded by amine aqueous solutions such as methylamine between 20–100°C	terephthalic acid, methylamine, ethylamine, sodium acetate, glacial acetic acid, potassium sulfate
Ammonolysis		PET is degraded by ammonia in an ethyl glycol environment at a temperature of 70°C	ammonia, carbamic acid, ethanolamine

Chemical recycling methods for cotton and natural fibers are less developed than methods for synthetics like nylon and polyester. Cotton is a cellulosic fiber, meaning it is derived from plants. Cellulosic fibers can be chemically recycled into a new fiber format called Man-Made Cellulosic Fibers (MMCF) (Fashion for Good, n.d.). Cotton can be chemically recycled into MMCF such as viscose, lyocell, and Ioncell. The methods to recycle virgin cotton fabrics into MMCF vary by their stage of development, level of industrialization, and potential for environmental impact.

Table 2 *Overview of polymer dissolution processes to chemically recycle cotton*

Polymer Dissolution Process	Description	Chemicals Used
Viscose[1,2]	Cotton fabric is depolymerized into a pulp and then converted to viscose; A majority of commercialized viscose processes utilize wood pulp as the cellulosic input; Highly toxic byproducts	carbon disulfide, zinc sulfate, cellulose xanthate, sulfuric acid
Lyocell[1,3]	Wood pulp or cotton fabric is dissolved in a solution of N-methylmorpholine oxide (NMMO) and dry-jet spun from the NMMO solution; Nearly 100% of NMMO is recovered; Requires high temperatures; Long processing times	N-methylmorpholine oxide (NMMO), propyl gallate
Ioncell[1,4]	Wood pulp or cotton fabric is dissolved in an ionic liquid (IL) solution and then wet or dry-jet wet spun; Ionic liquids are salts composed solely of ions with a melting point below 100°C	ionic liquids (IL)

[1] Ma et al., 2019; [2] Saha, 2020; [3] Haule, 2013; [4] De Silva et al., 2016

Regional Context in Vietnam

Vietnam was the fourth-largest exporter of clothing globally in 2022. The largest markets for garments manufactured in Vietnam were the United States, Japan, Korea, the United Kingdom, and Germany. There are over 6,000 garment factories in Vietnam, of which 4,200 (70%) produce ready-made garments (Le, 2017). With exports valued at $35 billion, Vietnam's textile and apparel industry employs more than 2.7 million people (World Trade Organization, 2023). Over 75%, or more than 2 million employees, are estimated to be women (BetterWork Vietnam, 2020). This thriving garment industry, however, also presents a challenge: managing the waste it generates. The following sections will explore Vietnam's waste management infrastructure, current environmental policies, and their impact on textile waste.

Waste Management Infrastructure

A country's waste management infrastructure comprises the systems and facilities responsible for collecting, transporting, processing, and disposing of waste. In Vietnam, this infrastructure is clustered around its urban centers in Hanoi and Ho Chi Minh City. Waste from residential and industrial sources is included in MSW. The primary end-point for about 71% of the collected MSW in Vietnam is landfill (Duc Luong et al., 2013; Verma et al., 2016). According to the Vietnamese Ministry of Natural Resources and Environment (MONRE), there were 904 landfills in 2019 (MONRE, 2020). In Vietnam, 17–20% of landfills are considered sanitary. The remaining locations are unsanitary landfills or community waste collection sites (Duc Luong et al., 2013; MONRE, 2004; MONRE, 2020). According to academic literature and government environmental reports, textile and fabric waste accounts for 2–7% of MSW in Vietnamese landfills (Duc Luong et al., 2013; MONRE, 2020).

In Vietnam, 13% of MSW is treated via incineration or burning (MONRE, 2020). As of 2019, there were 381 MSW incinerators in Vietnam. Approximately 23% of these facilities do not meet the National Technical Regulations for MSW Incinerators, meaning they do not have an exhaust gas treatment system or the system is not up to the policy's standard (MONRE, 2020). In a country where the waste management infrastructure cannot keep up with urbanization and population growth, a benefit of incineration is that it reduces MSW volume by 80–90% (Tong et al., 2021). Only a few incineration facilities in Vietnam can convert combustible waste to electricity. These waste-to-energy facilities are rare because of the high initial investment, operating costs, and technical requirements. Additionally, Vietnam's MSW composition has a high moisture content, posing a challenge for the combustion process (Duc Luong et al., 2013; MONRE, 2020).

Approximately 8–12% of MSW in Vietnam is recycled (Duc Luong et al., 2013; Hoang & Fogarassy, 2020). Recycling occurs through an informal network of scrap pickers, dealers, craft villages, and recycling facilities (Figure 3). Scrap pickers collect and sort recyclable materials directly from household waste bins, transport vehicles, and dump sites. These pickers then sell their waste to scrap dealers as intermediaries to the craft villages and recycling facilities. Craft villages and recycling facilities process and recycle materials into new products or separate, bale, and sell the materials to the processing industry (Tong et al., 2021; Van Den Berg & Duong, n.d.). This informal recycling sector diverts some discarded materials from landfills and provides employment in Vietnam (Tong et al., 2021).

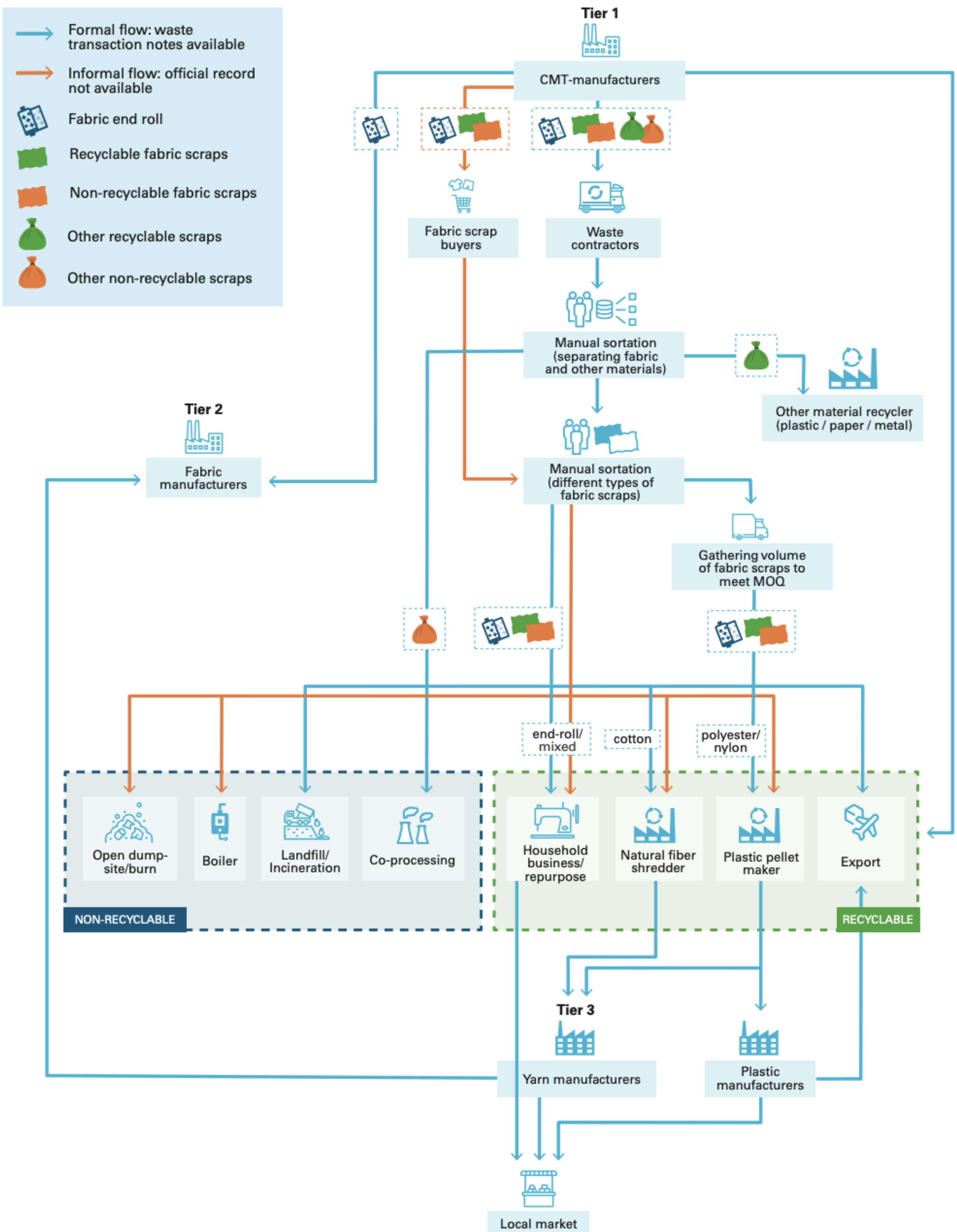

Figure 3 *Fabric waste flow chart in Vietnam apparel industry* (GCIC, 2022)

Environmental Policies and Targets

Administrative agencies within the executive branch of the Vietnamese government implement public policy. In the past, seven agencies were jointly responsible for managing solid waste in the country. However, in 2019, the MONRE was given the express authority to oversee the statewide waste management strategy (Trinh et al., 2021).

The Prime Minister approved the National Strategy on Integrated Waste Management in 2019 (Decision No.491/QĐ-TTg). It was authored by MONRE and the Ministry of Construction. This plan focuses on four management strategies to strengthen solid waste management both in the short term (2025) and the long term (2050):

- Strengthen waste management infrastructure, including waste collection, transportation, and treatment, while promoting reuse and recycling.
- Expand the network of solid waste collection.
- Promote reducing waste generation in daily life and business.
- Encourage proper waste sorting upon initial disposal.
- Attract foreign and private investments in domestic solid waste management.

This strategy highlights the goal of improving waste infrastructure amid population growth and increasing levels of waste generation. However, it is a target, and as of 2021 there were no policies or regulations to accompany it (MONRE, 2020; Tong et al., 2021; Trinh et al., 2021). In 2022, Vietnam's Deputy Prime Minister Le Minh Khai signed Decision 687 to develop a national circular economy plan and reduce plastic waste. However, the plan does not explicitly address textile waste (Vietnam Briefing News, 2022).

The MONRE also promulgates technical regulations. In 2016, the national technical standards for solid waste incineration went into effect (QCVN 61-MT: 2016/BTNMT). This standard outlines the requirements for constructing and operating incineration facilities in the country. It also includes a formula for the maximum pollution permitted for nine compounds: dust, hydrochloric acid, carbon monoxide, sulfur dioxide, nitrogen oxides, mercury, cadmium, lead, and general dioxide. A regional coefficient is applied in this calculation, meaning the maximum allowable value changes depending on the location of the incineration facility. One-fifth of Vietnam's incinerators do not meet these technical requirements (Enactment of Technical Regulation on the Environment, 2016; MONRE, 2020).

Methods

The project required four components to meet the three objectives. The data managers worked with the client over the summer to execute the waste quantification for objective one. For the second objective, the team engaged with their advisors and PhD mentor to strategize the most effective approach, leveraging the available data. A three-pronged methodology emerged: a comprehensive literature analysis, LCA synthesis, and a disposal fate scenario model. Lastly, research was conducted on Vietnam's waste management policies and disposal options to be included in the final recommendation.

Cut-and-Sew Waste Quantification

Pre-consumer textile waste from Patagonia's Tier 1 facilities in Vietnam was calculated using data from three primary sources. The overall material waste reported by factories was documented in the 2022 Higg Facility Environmental Module (Higg FEM) Waste data. This waste is representative of all brands that utilize these factories. The overall amount of material necessary for Patagonia products was calculated using data from Patagonia's Product Line Management (PLM) software. This software contains material characteristics input by the client's textile engineers and product developers. The amount of material wasted was calculated using marker efficiencies provided directly by the factory or an estimated range suggested by Patagonia's Senior Pattern Engineers. In order to obtain the most complete and current estimation of waste, all data were acquired from the Fall and Spring 2022 product seasons.

Higg Facility Environmental Module Data

Cascale's (formerly the Sustainable Apparel Coalition) Higg Index is a tool industry leaders utilize to measure sustainability within their value chain. The Higg FEM is an assessment tool hosted on Wordly, designed to assess the environmental impact of manufacturing facilities. All Patagonia facilities fill out this questionnaire annually, and a third party verifies their responses. With the help of Patagonia's Environmental Impact Team, Higg FEM Waste data from 2022 were extracted from the Worldly Platform. This was used to calculate the total reported amount of 'material waste' from Patagonia's final goods factories in Vietnam.

Product Line Management (PLM) Software

The PLM software is designed to assist in the planning, development, and management of products throughout their lifecycle. Among its many uses for the company, the team calculated the total material weight needed to make garments in Vietnam facilities in 2022.

In the PLM software, the team selected fields that provided the following data:

- Products manufactured in Vietnam during the Fall and Spring 2022 seasons
- Factories in which the products were manufactured (anonymized for this report)

- Total amount of units sold during the selected seasons
- Colorway (the product color or pattern)
- Material type
- The finished weight of the garment for each style sold
- Width of the fabric roll used for each style and colorway
- Yield for each garment (the length of fabric needed to produce each garment)
- Unit of measure for yield
- Placement of fabric (main body, liner, etc.)

Using the fields above, the team calculated the total material weight in grams of each style and colorway by multiplying the cuttable width (m) by the yield (m) to find the area of fabric required to produce the garment. The team then multiplied the fabric area required by the garment's finished weight (g/m^2) to determine the weight of the fabric used (Figure 4). Once the team had the total weight of material needed for each style and colorway, this weight was multiplied by the total number of units sold. Finally, the team summed all weights to find the total weight of fabric needed to produce garments during the Fall and Spring 2022 seasons in Vietnam.

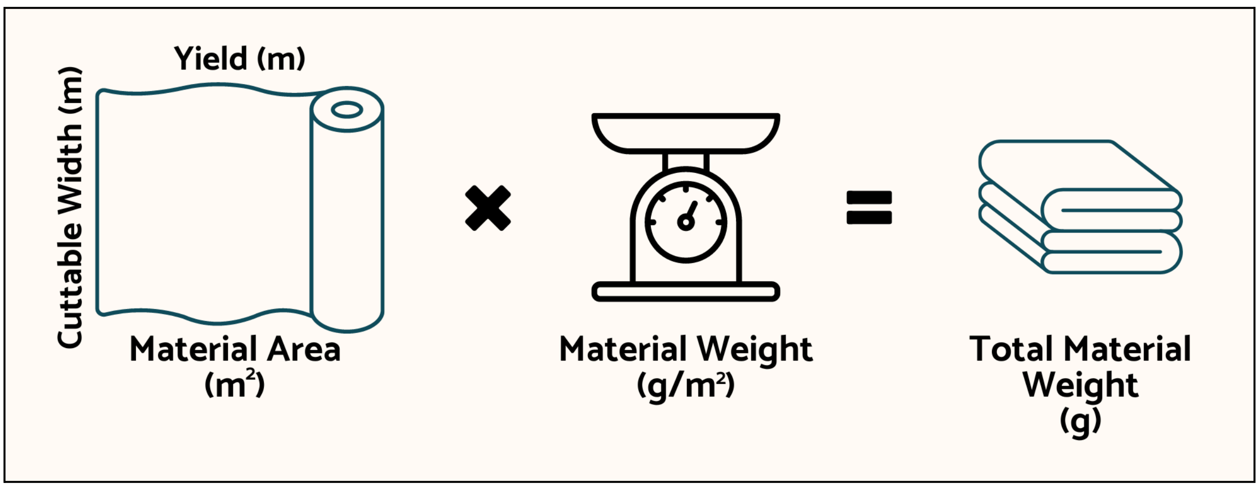

Figure 4 *Waste quantification method diagram* (Abou-Chakra et al., 2023)

Marker Efficiencies

A marker is a piece of paper that acts as a stencil to guide where sections of a garment should be cut from fabric. Marker efficiency is the percentage of material used in manufacturing a garment that ends up in the final product (See Figure 5).

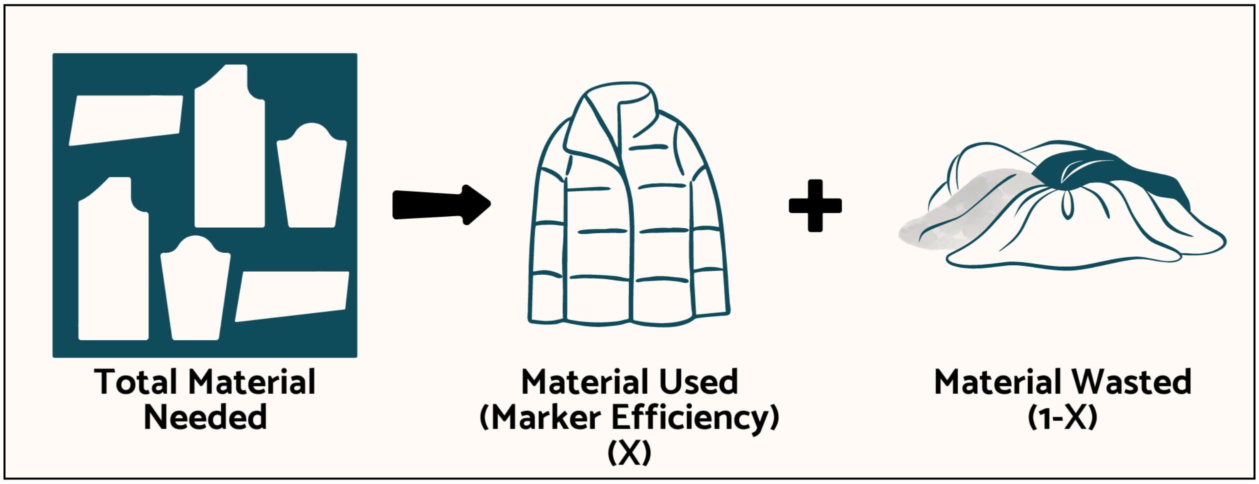

Figure 5 *Marker efficiency diagram* (Abou-Chakra et al., 2023)

Four of the 19 factories in Vietnam supplied marker efficiency data directly for the styles and colorways produced during the 2022 Fall and Spring seasons. For the remaining styles, the team worked with Senior Pattern Engineers from Patagonia to estimate a range for the marker efficiency (see Assumptions). These data were reported in percentages.

The team calculated the amount of fabric used in the final product by multiplying the total fabric weight for each garment (calculated from PLM) by the marker efficiency percentage. The team repeated this process using the low end of the marker efficiency range, the high end of the range, and the average of the two estimated by the Senior Pattern Engineers. The team then subtracted this value from the total weight of the fabric to determine the amount of fabric wasted in manufacturing the garment. The wasted material was then summed to find the total amount of fabric wasted in Vietnam during the 2022 Fall and Spring seasons.

Assumptions

1. All products are base size:
    a. Men: Medium
    b. Women: Small
    c. Kids: M (10)
    d. Baby: 2T
    e. Infant: 12 months
2. There is no variability in marker efficiencies of the same product.
3. All marker efficiencies are the same as the main body component.
4. All marker efficiencies received from factories are accurate and consistent.
5. Based on their knowledge of similar styles, marker efficiencies that were not provided directly from the facility were estimated by Senior Pattern Engineers.
6. All factory textile waste is being landfilled or incinerated.

Supplier Survey

A survey for suppliers was designed to supplement the information provided in the Higg FEM results and further understanding of the current waste management practices in Vietnam. Patagonia sent the survey through their supply chain management and communication tool (CR360). An initial email was sent to suppliers, providing context to improve their awareness and increase their willingness to participate. Appendix C includes the list of questions.

Impact Analysis

The team engaged with subject-matter experts to strategize the assessment of environmental and public health impacts linked to the four selected disposal methods: landfill, incineration, mechanical recycling, and chemical recycling. After discussions with experts and the client, it became clear that an investigation into these impacts required the use of secondary data. Although LCAs can provide product-specific impact data, they fail to capture all potential impacts. Additionally, end-of-life LCAs for the three material types and four disposal methods are scarce. Ultimately, the team combined a literature synthesis with an LCA synthesis to understand the potential environmental and public health impacts of textile waste.

Environmental & Health Impact Literature Synthesis

The environmental and health impact literature synthesis was conducted in three steps:

1. The group set a foundation for capturing data from the literature and established guardrails on which literature would be included or excluded.
2. Group members independently reviewed the literature, recording secondary qualitative data that linked environmental and public health impacts with each disposal method.
3. Impact data were synthesized by grouping them into larger impact categories.

Literature Search and Selection Process

Building on the preliminary findings, the team developed a framework for the literature synthesis to address environmental and public health consequences related to textile waste disposal. Recognizing the lack of textile-specific waste data, studies on solid waste were included. The team aimed to exclude impacts unrelated to textiles from the results. For a study to be included, a link had to be established between an environmental or public health impact and one of the four disposal methods within our project's scope. Priority was given to articles published from 2013–2023 for their contemporary relevance while remaining open to older articles containing pertinent information. Although the initial preference was to source research from Vietnam or nearby regions, this was too limiting, so global research was used.

The team used UCSB Library's journal article database. Each team member focused on researching a specific disposal method. Data were compiled in a spreadsheet where the waste type, geographical location, impacts, search terms used, article details, and corresponding links were documented. See Table 3 for the search terms used and the number of studies selected.

Table 3 *Search terms and studies (reviewed vs. selected) for environmental and health impact literature synthesis*

Disposal Method	Studies Reviewed	Studies Selected	Search Terms Used
Landfill	25	5	health impacts landfills, impacts of textiles in landfills
Incineration	19	5	apparel incineration effects, incineration environmental impacts, incineration health impacts, cotton incineration, polyester incineration, nylon incineration
Chemical Recycling	15	4	cotton to lyocell chemical recycling, impacts of pyrolysis based recycling, impacts of pyrolysis based recycling textiles, environmental impacts of pyrolysis based recycling textiles, textile-to-textile recycling cotton textile-to-textile recycling nylon textile-to-textile recycling polyester
Mechanical Recycling	24	2	textile mechanical recycling mechanical recycling impacts mechanical recycling cotton mechanical recycling polyester mechanical recycling nylon environmental impacts mechanical recycling health impacts mechanical recycling textile recycling impacts recycled nylon impacts recycled polyester impacts textile reuse impacts

Impact Data Collection

Articles that met the team's criteria were further reviewed, and any impacts of the disposal method were parsed out. The impacts were cataloged into a table, along with their corresponding disposal method, material type, and bibliographical information.

For chemical recycling, impacts were established based on the catalysts and solvents used in the various chemical recycling processes. The safety data sheet (SDS) of each chemical was reviewed for human health and environmental impacts. Human health impacts were recorded from the Hazards Identification section unless the chemical was also listed as a carcinogen later in the report. Environmental health impacts were recorded from the Ecological Information section of the SDS report. See Table 4 for how these impacts were categorized within the results.

Table 4 *Categories of impacts from solvents used in chemical recycling*

Impact Category	Description
Corrosion	Serious eye damage/irritation Skin corrosion/irritation
Acute Toxicity	Acute toxicity: oral, dermal, or inhalation of vapors Respiratory system toxicity (single exposure) Central nervous system toxicity (single exposure) Specific target organ toxicity (single exposure)
Health Hazards	Organ toxicity: central nervous system, liver, kidney, heart, blood, respiratory system Target organs: kidneys, heart, liver, lungs, eyes Specific target organ toxicity (repeated exposure) Germ cell mutagenicity Carcinogenicity Reproductive toxicity Liver and kidney toxicity (repeated exposure) Causes eye and skin irritation and possible burns Causes digestive and respiratory tract irritation with possible burns Harmful if swallowed or absorbed through the skin Respiratory sensitization Skin sensitization
Environmental Impact	Very toxic to aquatic environments Large amounts will affect pH and harm aquatic organisms Harmful to aquatic organisms Toxic to aquatic organisms May cause long-term adverse effects in the environment

Impact Grouping

Once the literature search and selection process was complete, impact data were categorized into environmental and health impacts based on Life Cycle Impact Assessment (LCIA) impact endpoint levels (EC-JRC 2010). Any negligible (as defined by the study) or out-of-scope impacts (e.g. not about textile waste) were omitted. Impacts relating to multiple categories were included in all relevant categories. Once fully categorized, the impact data were compiled into a results table.

The two impact categories were broadly defined as follows:

- Natural Environment: climate change, ozone depletion, ionizing radiation, photochemical ozone formation, acidification, eutrophication (aquatic and terrestrial), ecotoxicity, land use, resource depletion (see Table 5)
- Human Health: climate change, ozone depletion, human toxicity (carcinogenic and non-carcinogenic), respiratory particles and inorganics, ionizing radiation, and photochemical ozone formation (see Table 6)

Table 5 *Categories of impacts to the natural environment from literature synthesis*

Disposal Method	Impact Category	Description(s)
Landfill	Acidification	Sulphates
	Air pollution	Air pollution
	Climate change	Methane (CH_4), Nitrogen dioxide (NO_2)
	Heavy Metals	Copper (Cu), Iron (Fe), Lead (Pb)
	Eutrophication	Phosphates
	Odor Pollution	Hydrogen sulfide (H_2S)
	Water Pollution	Underground water pollution
Incineration	Acidification	Acidic gasses Hydrochloric acid (HCl)
	Air pollution	Dry flue gas, Fly ash, Flue gas: CO_2, CO, CH_4, NO_x, SO_2, H_2S, HCl, HF, PM 10, Hg, Pb, Cr, Ni, Nitrous oxides (NO_x), Particular matter (PM), Slag
	Climate change	Carbon monoxide (CO), Carbon dioxide (CO_2), Ethane, Ethene, Methane (CH_4)
	Heavy metals	Cadmium (Cd), Mercury (Hg)
Mechanical Recycling	Acidification	Sulfur dioxide equivalent (SO_2e)
	Air pollution	non-methane volatile organic compounds (NMVOC equivalent)
	Climate change	Carbon dioxide equivalent (CO_2e)
	Eutrophication	Phosphates

Table 6 *Categories of impacts to human health from literature synthesis*

Disposal Method	Impact Category	Description(s)
Landfill	Air pollution	Air pollution
	Carcinogens	Dioxins: polychlorinated dibenzo-p-dioxins (PCDD), polychlorinated dibenzofurans (PCDF), and polycyclic aromatic hydrocarbon (PAHs), Naphthalene, Trichloropropane, Trimethylbenzene
	Climate change	Methane (CH_4), Nitrogen dioxide (NO_2)
	Eye irritation	Eye irritation
	Odor pollution	Hydrogen sulfide (H_2S), Odor pollution
	Respiratory illness	Flu, Respiratory infections
	Water pollution	Underground water pollution
Incineration	Air pollution	Fly ash, Flue gas: CO_2, CO, CH_4, NO_x, SO_2, H_2S, HCl, HF, PM 10, Hg, Pb, Cr, Ni, Nitrous oxides (NO_x), Particulate matter (PM), Slag, Sulfur dioxide (SO_2)
	Carcinogens	Dioxins: PCDD and PCDFs
	Climate change	Carbon monoxide (CO), Carbon dioxide (CO_2), Ethane, Ethene, Methane (CH_4)
	Respiratory illness	HCl
	Heavy metals	Mercury (Hg)
Mechanical Recycling	Air pollution	non-methane volatile organic compounds (NMVOC equivalent)
	Climate change	Carbon dioxide equivalent (CO_2e)

Environmental & Health Indicator LCA Synthesis

The team began to synthesize environmental and health indicators in textile LCAs by setting the foundation for what would be included and excluded. The team then gathered relevant LCAs and pulled end-of-life data into a spreadsheet. Finally, the collected secondary data were standardized to ensure comparability. The resulting standardized data were crucial for achieving a comprehensive and accurate synthesis of LCA results.

The primary purpose of an LCA is to determine the environmental impacts associated with a product or process. The assessment is conducted in four general steps: goal and scope definition, inventory analysis, impact assessment, and interpretation of the results. Inventory analysis breaks down the production of the product into unit processes and determines the inputs, outputs, and associated environmental impacts of each step. Each LCA has a functional or quantified reference unit to maintain a standard for analysis and make results comparable. Environmental indicators measure impact with values presented in standard equivalence units. The equivalence units correspond to specific impact categories; for example, kilograms of CO_2e (kg CO_2e) measure global warming potential. Common impact categories include global warming potential, acidification potential, eutrophication potential, human toxicity, and water depletion. This assessment can be conducted from cradle-to-grave, meaning from product fabrication to end-of-life, or from cradle-to-gate, meaning from product fabrication to the factory gate. A cradle-to-gate LCA excludes the use-phase and end-of-life impacts of a product. In order to analyze the impacts of disposal methods, this project focused on cradle-to-grave LCAs.

LCA Search and Selection Process

Following the model of the literature synthesis, the team established criteria for LCAs to be used in this study. Knowing that LCAs with end-of-life data are rare, the study was open to LCAs from any year and location. Given that LCAs are product-specific, only those with the disposal of cotton, nylon, and polyester through the four selected disposal methods were included. Consistent with the literature analysis, UCSB Library's journal article database was used, in addition to Google Scholar. Throughout the search, the number of LCAs reviewed was tracked, and only those with end-of-life were utilized.

The search terms used in both Google Scholar and the UCSB Library Article Database were:

- Impacts of pyrolysis-based recycling
- Impacts of textiles in landfills
- Cotton end-of-life LCA
- Environmental impacts of advanced recycling of textiles
- Nylon life cycle assessment/Nylon LCA
- Cotton life cycle assessment/Cotton LCA
- Polyester life cycle assessment/Polyester LCA

Table 7 *LCAs reviewed compared to the LCAs that could be utilized highlights the gap between end-of-life data in LCAs*

LCAs Reviewed	LCAs Utilized
58	12

Impact Category Selection

Impact categories with a single score value, such as human health or ecological footprint, were omitted. These categories are calculated by measuring the annual impact load and dividing it by a population average, resulting in a per capita impact measured in a point system. These impact categories were only encountered within one study and were omitted because the point values alone, without comparison, do not provide helpful information. Any variable end-of-life scenario with multiple disposal methods, such as 35% landfill, 60% incineration, and 5% reuse, were omitted as the exact values associated with each disposal method could not be parsed from the reported value.

Data Collection

LCA studies that met the above criteria were further reviewed, and any quantitative measures of end-of-life impacts were parsed out. The quantitative impact values were documented within a table consisting of material type, disposal method, environmental or health indicator category, functional unit (FU), and associated bibliographical information.

Standardization and Synthesis

Once the LCA selection was complete, material type was categorized based on the majority component into one of the following: polyester, cotton, nylon, or poly-cotton blend. Any disposal methods that were a mixture of two or more distinct methods were omitted for clarity. Any reuse was also omitted because it models post-consumer fabric, which is outside this project's scope.

Impact indicator names were adjusted to maintain consistency, and any necessary unit conversions were made for consistency. Incineration with WTE or heat recovery was grouped into one disposal type as “incineration—waste to energy.” Global Warming Potential (GWP) indicators from different studies were calculated using different Assessment Report values from the Intergovernmental Panel on Climate Change (IPCC). All functional units were converted to 1 tonne of material, and impacts were scaled accordingly.

Disposal Fate Modeling

Due to the lack of literature on the environmental and health impacts of waste disposal in Vietnam, both in academic research and LCA studies, the team built models to simulate emissions from cotton, polyester, and nylon degrading in a landfill without gas capture and incineration without energy recovery. The team used LCA for Experts Version 10.7.1.28, produced and operated by Sphera, to model Vietnam's energy grid and the incineration models. Any data utilized within LCA for Experts processes are from the Sphera database within the software version.

Model of Vietnam's Energy Grid

To simulate the impact of the current energy grid in Vietnam, a model was created in LCA for Experts using the country's 2021 breakdown of energy sources. The model was scaled to 1 kWh with each source process (e.g., coal, oil, etc.) input as its equivalent to the percent of the grid makeup (see Table 8). The source processes were funneled through an intermediary process (i.e., Vietnam's Energy Grid), and all impacts were calculated using TRACI 2.1 (see Appendix B Figure B-1 for model structure).

Table 8 *Vietnamese energy grid source breakdown* (IEA, 2021)

Source	Percent Contribution
Coal	49.1%
Oil	24.1%
Biofuels and Waste	10.2%
Hydro	7.1%
Natural Gas	6.6%
Wind and Solar	2.9%

Landfill Emissions Simulation

The only available landfill processes in the Sphera database were sanitary landfills that capture gas for energy. Due to the lack of comparable landfill models, the team utilized an alternative approach to estimate landfill emissions based on the carbon content in cotton, polyester, and nylon. The carbon content was calculated using the ratio of the molar mass of carbon within the material's chemical compound and the total molar mass of the chemical compound (see Table 9). The team simulated the decomposition of each material within a landfill scenario using the carbon content by assuming that 50% of the carbon would become carbon dioxide and the other 50% methane (US EPA, 2016a). This assumption presents only one possible scenario; actual results would differ based on landfill management and conditions. In addition, the time required for the complete decomposition of the cellulose in cotton, if decomposition were to be complete, is unknown, and could be decades, or longer.

Using a functional unit of 1 tonne of textile waste, the team multiplied the carbon content percentage by the functional unit to find the amount of carbon for each material type. This amount was then divided in half to model how much carbon would become carbon dioxide and methane. Because nylon and polyester are not biodegradable, the carbon content within these materials does not decompose the way that cotton does and is considered inert or unreactive in a landfill.

Table 9 *Carbon content of cotton, nylon, and polyester*

Material	Compound	Molar Mass of Carbon	Total Molar Mass	Carbon Content (%)
Cotton	Cellulose ($C_6H_{10}O_5$)	72.07	162.14	44.5%
Nylon	Caprolactam ($C_6H_{11}NO$) Crotetamide ($C_{12}H_{22}N_2O_2$)	144.13	226.32	63.7%
Polyester	PET ($C_{10}H_8O_4$)	120.11	192.17	62.5%

Incineration Analysis

The team used outputs from 'RER: Textiles in municipal waste incineration plant' in LCA for Experts to estimate the impacts of incineration. The process was modified to exclude energy and steam creation, modeling incineration without energy capture as is the case in Vietnam. The process in LCA for Experts is based on the average municipal solid waste incineration facilities in Europe and assumes the textile being incinerated has a net calorific value of 21 MJ/kg. Impacts of incineration were calculated using TRACI 2.1.

Regional Context Assessment

In order to ensure the recommendation to the client was feasible, the team conducted research into the context of the project in Vietnam. This research was conducted as part of the initial literature review and consulted academic papers, government reports, and technical regulations.

Results

Cut-and-Sew Waste Quantification

Utilizing the data available from Higg FEM assessment results, the 19 Tier 1 Facilities in Vietnam reported a range of 8.4–2,390 tonnes of textile waste overall for the Fall and Spring 2022 seasons.

According to Patagonia's PLM software, approximately 10 million units of product were created, requiring around 3,500 tonnes of materials to make. Of that, 2,727–2,916 tonnes were used within the final product, while approximately 16–21% was wasted (Table 10, Figure 6). Of the average total material wasted based on marker efficiency calculations, most of the waste was polyester, followed by nylon, cotton, and blends (see Figure 7).

Table 10 *Material usage based on marker efficiency ranges*

	Low Efficiency	High Efficiency	Average
Material Used	2,730 tonnes	2,920 tonnes	2,820 tonnes
Material Wasted	740 tonnes	550 tonnes	640 tonnes
Total Material*	3460 tonnes	3460 tonnes	3460 tonnes
Percent Wasted	21%	16%	18%

* Sum of Material Used and Material Wasted may not equal Total Material due to rounding

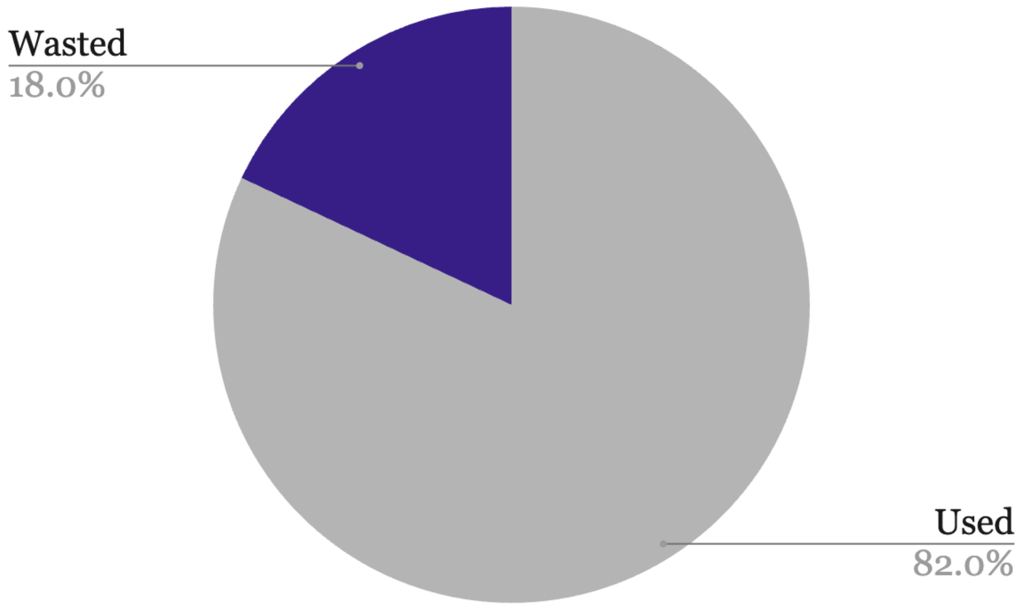

Figure 6 *Total average material fate of all necessary material (~3500 tonnes). Dark purple represents utilized fabric (82%) and gray represents wasted fabric (18%).*

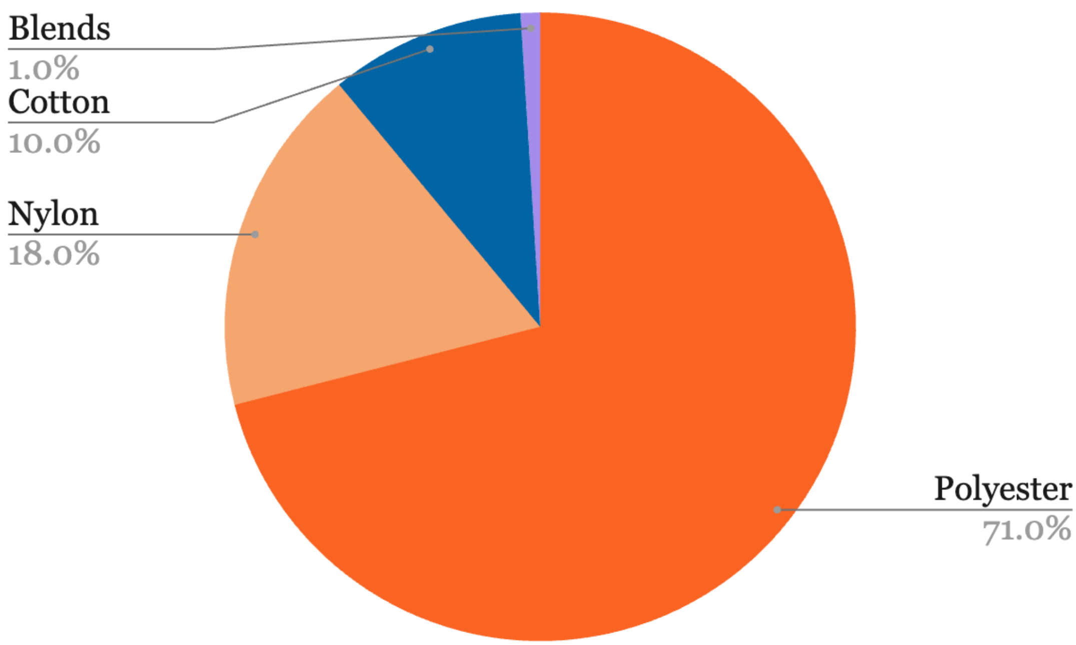

Figure 7 *Total material wasted by material type (based on average marker efficiency calculations). Dark orange is polyester (71%), blue is cotton (10%), light orange is nylon (18%), and light purple is a blend of the three dominant material types (1%). Materials were categorized based on their dominant (>50%) material type.*

Supplier Survey Results

The survey received a 100% response rate from targeted suppliers. Survey responses indicated that no suppliers incinerate on site or send material directly to landfill. Instead, most facilities have contracted agreements with waste haulers who collect and transport their fabric waste. Suppliers stated the primary influence over their textile disposal method was 'Local Policies and Regulations' followed by 'Cost.' The survey responses also included a list of the waste hauler companies utilized by factories. When the team researched these third-party haulers, they could not identify any additional information on the type of waste or mode of disposal the company specialized in. Waste hauler information is not included in this report to protect supplier confidentiality. For further details, please see Appendix C.

Impact Analysis

Associated Impacts from Literature Synthesis

After synthesizing the literature, the team identified seven impacts on the natural environment associated with landfills and four impacts each for incineration and mechanical recycling. Only three of the impacts were associated with cotton textile waste. The rest were found in literature regarding unspecified MSW. See Table 11 for categorized results of impacts to the natural environment (see Tables B-1 through B-3 in Appendix B).

Landfill was found to have seven impacts on human health, followed by incineration with six, and mechanical recycling was found only to have two associated impacts. Two of these results were from studies on cotton textile waste, and all others were associated with unspecified MSW. See Table 12 for categorized results of impacts on human health (see Tables B-4 through B6 in Appendix B).

For chemical recycling, Safety Data Sheets of 28 solvents were reviewed. Impacts were categorized into four categories: corrosion, acute toxicity, health hazards, and environmental (see Table B-7 in Appendix B). Of the 28 solvents, 19 had corrosion impacts, 18 had acute toxicity impacts, 26 had health hazard impacts, and 21 had environmental impacts (see Table 13).

Table 11 *Impacts to the natural environment associated with landfill, incineration, and mechanical recycling*

Impacts to Natural Environment		
Landfill	**Incineration**	**Mechanical Recycling**
Acidification[1]	Acidification[2, 3, 4]	Acidification* [5]
Air pollution[6]	Air pollution[2, 3, 4, 7]	Air pollution[8]
Climate change[9]	Climate change* [3, 4, 7, 10]	Climate change* [5, 8]
Heavy metals[1]	Heavy metals[2, 7]	-
Eutrophication[1]	-	Eutrophication* [5]
Odor pollution[11]	-	-
Water pollution[6]	-	-

* From studies regarding cotton textile waste, all others refer to impacts from unspecified MSW
[1] Paul et al. 2019; [2] Dilshani et al. 2019; [3] Dan et al. 2023; [4] Lu et al. 2017; [5] Esteve-Turrillas and de la Guardia 2017; [6] Siddiqua et al. 2022; [7] Dong et al. 2018; [8] Harish et al. 2021; [9] Njoku et al. 2019; [10] Molto et al. 2005; [11] Wu et al. 2018

Table 12 *Impacts to human health associated with landfill, incineration, and mechanical recycling*

Impacts to Human Health		
Landfill	**Incineration**	**Mechanical Recycling**
Air pollution [1]	Air pollution [2, 3, 4, 10]	Air pollution [5]
Climate change [6]	Climate change* [4, 7]	Climate change* [5, 8]
Respiratory illness [6]	Respiratory illness [3, 4]	-
Carcinogens [6, 9]	Carcinogens [2, 3, 4, 10]	-
Odor pollution [1, 9]	Mercury [4]	-
Water pollution [1]	Heavy metals [4, 10]	-
Eye Irritation [6]	-	-

* From studies regarding cotton textile waste, all others refer to impacts from unspecified MSW
[1] Siddiqua et al. 2022; [2] Dan et al. 2022; [3] Lu et al. 2017; [4] Dong et al. 2018; [5] Harish et al. 2021; [6] Njoku et al. 2019; [7] Molto et al. 2005; [8] Esteve-Turrillas and de la Guardia 2017; [9] Wu et al. 2018; [10] Dilshani et al. 2019

Table 13 *Impacts of chemical recycling*

Solvent	Process	Material Type(s)	Impact Category				Source
			Corrosion	Acute Toxicity	Health Hazards	Environmental	
AMIMICl[1]	lyocell	cotton	✓		✓		ThermoFisher Scientific, 2021i
ammonia	ammonolysis	polyester, nylon	✓		✓	✓	ThermoFisher Scientific, 2023f
carbamic acid	ammonolysis	polyester, nylon	✓		✓		ThermoFisher Scientific, 2021c
carbon disulfide	viscose	cotton	✓	✓	✓	✓	ThermoFisher Scientific, 2023a
cobalt acetate	methanolysis	polyester, nylon		✓	✓	✓	ThermoFisher Scientific, 2021a
ethanolamine	ammonolysis	polyester, nylon	✓	✓	✓	✓	ThermoFisher Scientific, 2021b
ethylamine	aminolysis	polyester, nylon			✓	✓	ThermoFisher Scientific, 2008
ethylene glycol	glycolysis	polyester, nylon		✓	✓	✓	ThermoFisher Scientific, 2021d
formic acid	acid hydrolysis	polyester, nylon	✓	✓	✓	✓	ThermoFisher Scientific, 2022
glacial acetic acid	aminolysis	polyester, nylon	✓		✓	✓	ThermoFisher Scientific, 2021l

Table 13 *Impacts of chemical recycling (continued)*

Solvent	Process	MaterialType(s)	Impact Category				Source
			Corrosion	Acute Toxicity	Health Hazards	Environmental	
hydrochloric acid	acid hydrolysis, alkaline hydrolysis	polyester, nylon	✓	✓	✓	✓	ThermoFisher Scientific, 2015a
lead oxide	methanolysis	polyester, nylon		✓	✓	✓	ThermoFisher Scientific, 2015c
magnesium acetate	methanolysis	polyester, nylon			✓		ThermoFisher Scientific, 2021e
methanol	methanolysis	polyester, nylon		✓	✓	✓	ThermoFisher Scientific, 2015b
methylamine	aminolysis	polyester, nylon	✓	✓			ThermoFisher Scientific, 2024
NMMO[2]	lyocell	cotton	✓		✓		ThermoFisher Scientific, 2020c
nitric acid	acid hydrolysis	polyester, nylon	✓	✓	✓	✓	ThermoFisher Scientific, 2021f
polyphosphoric acid	glycolysis	polyester, nylon	✓	✓	✓	✓	ThermoFisher Scientific, 2021g
potassium hydroxide	alkaline hydrolysis	polyester, nylon	✓	✓	✓	✓	ThermoFisher Scientific, 2023c
potassium sulfate	aminolysis	polyester, nylon			✓	✓	ThermoFisher Scientific, 2021m

Table 13 *Impacts of chemical recycling (continued)*

Solvent	Process	Material Type(s)	Impact Category				Source
			Corrosion	Acute Toxicity	Health Hazards	Environmental	
sodium acetate	aminolysis	polyester, nylon			✓	✓	ThermoFisher Scientific, 2021h
sodium glycolate	glycolysis	polyester, nylon					ThermoFisher Scientific, 2021j
sodium hydroxide	alkaline hydrolysis	polyester, nylon	✓	✓	✓	✓	ThermoFisher Scientific, 2023b
sulfuric acid	acid hydrolysis, alkaline hydrolysis	polyester, nylon	✓	✓	✓	✓	ThermoFisher Scientific, 2023d
terephthalic acid	neutral hydrolysis, aminolysis	polyester, nylon	✓	✓	✓	✓	ThermoFisher Scientific, 2020a
trifluoroacetic acid	acid hydrolysis	polyester, nylon	✓	✓	✓	✓	ThermoFisher Scientific, 2023e
zinc acetate	glycolysis, methanolysis	polyester, nylon	✓	✓	✓	✓	ThermoFisher Scientific, 2021k
zinc sulfate	viscose	cotton	✓	✓	✓	✓	ThermoFisher Scientific, 2020b

[1] 1-Allyl-3-methylimidazolium chloride
[2] n-methylmorpholine-N-oxide

Quantification of LCA Impacts from LCA Synthesis

Across all disposal types, the team found the highest number of LCAs conducted on cotton (n=6), followed by polyester (n=4), poly-cotton blends (n=3), and nylon (n=2). The results discussed and depicted below are the isolated end-of-life impacts of each material type. LCAs with location information available were located in Australia, China, Denmark, Netherlands, Sweden, Turkey, and the United States.

When reviewing the LCA impact results, it is essential to understand what the values represent. Positive values indicate that the functional unit creates an adverse externality on the environment. For example, if the impact is listed as 2,600 kg CO_2e, the functional unit emits that amount. A negative value indicates that the functional unit is responsible for an impact reduction. For example, if the impact listed has -600 kg CO_2e, the functional unit is responsible for reducing emissions by that amount.

The team's LCA synthesis results showed large differences between disposal methods. Across many of the studies below, there are avoided impacts by mechanically or chemically recycling the textile waste compared to incineration without energy recovery and landfilling. There are also avoided impacts for incineration with energy recovery when displacing energy sourced from fossil fuel. This gap can be attributed to the recycling process avoiding the need to produce virgin material and 'crediting' this impact reduction back to the process as a whole. This does not mean that recycling removes emissions, but it does lower the overall footprint of the product in comparison to alternative end-of-life methods. Meanwhile, material that is landfilled or incinerated without energy recovery cannot be used again in another product or reduce overall impact, so these results are much higher.

Acidification Potential

When mechanically recycled, cotton had the lowest impact on Acidification Potential (AP) with -14.76 kg sulfur dioxide equivalent (SO_2e). Disposing of cotton via landfill resulted in the highest impact with 2,280 kg SO_2e. There were no studies on the acidification impacts of chemically recycling or incinerating cotton (with or without energy recovery).

Chemically recycling polyester had a significantly lower impact on AP with 0.16 kg SO_2e than when disposed of by landfill with 1,850 kg SO_2e. There were no studies on the acidification impacts of mechanically recycling or incinerating polyester (with or without energy recovery).

The only result available for the acidification impact of disposing of poly-cotton blends was 0.13 kg SO_2e from landfilling. The acidification impact of landfilling poly-cotton blends was significantly lower than that of other material types because that particular study included an energy credit for methane generation, whereas the other studies did not (Moazzem et al., 2021b). There were no studies on incineration (with or without energy recovery), mechanical recycling, or chemical recycling of poly-cotton blends.

There were no results from studies on the acidification impacts of disposing of nylon via landfill, incineration (with or without energy recovery), mechanical recycling, or chemical recycling.

Agricultural Land Occupation

When mechanically recycled, cotton had a significantly lower impact on Agricultural Land Occupation (ALO) of -3,671.85 m^2a. When landfilled, cotton had an impact of 120 m^2a. There were no studies on ALO impacts of cotton when incinerated (with or without energy recovery) or chemically recycled.

The ALO impact associated with disposal of polyester was significantly lower when chemically recycled at 1.27 m^2a versus when landfilled at 2,510 m^2a. There were no results from studies on ALO impacts of polyester when incinerated (with or without energy recovery) or mechanical recycled.

The only available result for ALO impact associated with disposal of poly-cotton blends was -0.02 m^2a from landfilling. The ALO impact of landfilling poly-cotton blends was significantly lower than that of other material types because the study included an energy credit for methane generation, whereas the other studies did not (Moazzem et al., 2021b).

There were no studies on the ALO impacts associated with the disposal of nylon via landfill, incineration (with or without energy recovery), mechanical recycling, or chemical recycling.

Eutrophication Potential

There were only results on Aquatic Eutrophication Potential (AEP) and Terrestrial Eutrophication Potential (TEP) for cotton incineration without energy recovery. Incinerating cotton without energy recovery resulted in an AEP impact of 0 kg NO_3^- and a TEP impact of 50 kg NO_3^-.

There were no results from studies regarding the AEP or TEP impacts associated with the disposal of polyester, nylon, or poly-cotton blends via landfill, incineration with energy recovery, mechanical recycling, and chemical recycling.

Global Warming Potential

When mechanically recycled, cotton had a significantly lower impact on GWP with -1502.43 kg CO_2e. Disposing of cotton via landfill or incineration without energy recovery resulted in the highest impact on GWP. There was variation in results between the two studies for the impact when landfilled, ranging from 700–2,600 kg CO_2e. Limited context was provided within these studies to discern specific causes for the two divergent values. The larger range, 2,600 kg CO_2e, contained an assumed 20 km of transportation and utilized energy grid data from China (Moazzem et al., 2021a). The smaller range, 700 kg CO_2e, did not provide further explanation outside of describing the values as isolated landfill impacts modeled with the aid of Simapro Ver 7.2 (Muthu et al., 2012). Incineration of cotton without energy recovery resulted in 2,000 kg of CO_2e. However, in a study of incinerating cotton with energy recovery, the results indicated a significantly lower impact of -820 to -600 CO_2e. There were no results from studies on the impacts of chemically recycling cotton.

When mechanically recycled, nylon had the lowest impact on GWP with 192.47 kg CO_2e. However, it had the highest impact at 700 kg CO_2e, when disposed of via landfill. There were no studies on the impacts of incinerating or chemically recycling nylon.

Polyester had the lowest impact on GWP with -900 to -267.73 kg CO_2e when chemically recycled and the highest impact when landfilled with 700–1,520 kg CO_2e. This range is provided by the same two studies where limited context was provided to discern specific differences between the values mentioned in the cotton results above. The two studies do not provide sufficient content to warrant unique differences (Moazzem et al., 2021a; Muthu et al., 2012). There were no results from studies on the impacts of incinerating or mechanically recycling polyester.

Poly-cotton blends had the lowest impact on GWP with -5,500 kg CO_2e when chemically recycled. The highest impact disposal method of poly-cotton blends varied based on the study. When disposed of via landfill, poly-cotton blends had an impact of -127.5 kg CO_2e. The GWP impact of landfilling poly-cotton blends was negative because the study included energy credit of methane generation, whereas the other studies did not (Moazzem et al., 2021b). When incinerated with energy recovery, poly-cotton blends resulted in -1,040–230 kg CO_2e. Both studies report the GWP impact of incinerating poly-cotton blends with energy recovery incorporated credits from the avoided energy use (Koligkioni et al., 2018; Zamani et al., 2015). The range in GWP impact is likely due to the difference in energy sources that are being displaced. In Denmark, the location of the study reporting -1,040 kg CO_2e, 54.1% of the energy grid supply is from fossil fuels (IEA, 2022a). In contrast, the study reporting 230 kg CO_2e is from Sweden where 23.3% of the energy grid supply is from fossil fuels (IEA, 2022b). Displacing energy from fossil fuel sources will result in a more significant impact reduction from GHG displacement.

Water Depletion

Mechanically recycling cotton had a significantly lower impact on water depletion, with -860.62 m^3 compared to 80 m^3 when landfilled. There were no studies regarding the water depletion impacts of incineration (with or without energy recovery) or chemical recycling cotton.

Chemically recycling polyester had a significantly lower impact on water depletion with 0.29 m^3 compared to 15,890 m^3 when landfilled. There were no studies regarding how incineration (with or without energy recovery) and mechanical recycling impacts water depletion.

There were no studies regarding water depletion impacts of nylon and poly-cotton blends when landfilled, incinerated (with or without energy recovery), mechanically recycled, or chemically recycled.

See Tables 14–18 for impacts of LCA indicators for landfill, incineration without energy recovery, incineration with energy recovery, mechanical recycling, and chemical recycling.

Table 14 *Impacts of landfill (FU = 1 tonne textile waste)*

Material	Indicator	Impact	LCA Location	Source
Cotton	Acidification Potential	2,280 kg SO_2e	Australia	(Moazzem et al., 2021a)
	Agricultural Land Occupation	120 m^2a	Australia	(Moazzem et al., 2021a)
	Global Warming Potential	2,600 kg CO_2e	Australia	(Moazzem et al., 2021a)
		700 kg CO_2e	Unavailable	(Muthu et al., 2012)
	Water Depletion	80 m^3	Australia	(Moazzem et al., 2021a)
Nylon	Global Warming Potential	700 kg CO_2e	Unavailable	(Muthu et al., 2012)
Polyester	Acidification Potential	1,850 kg SO_2e	Australia	(Moazzem et al., 2021a)
	Agricultural Land Occupation	2,510 m^2a	Australia	(Moazzem et al., 2021a)
	Global Warming Potential	1,520 kg CO_2e	Australia	(Moazzem et al., 2021a)
		700 kg CO_2e	Unavailable	(Muthu et al., 2012)
	Water Depletion	15,890 m^3	Australia	(Moazzem et al., 2021a)
Poly-Cotton Blend	Acidification Potential	0.13 kg SO_2e	Australia	(Moazzem et al., 2021b)
	Agricultural Land Occupation	-0.02 m^2a	Australia	(Moazzem et al., 2021b)
	Global Warming Potential	-127.5 kg CO_2e	Australia	(Moazzem et al., 2021b)

Table 15 *Impacts of incineration without energy recovery (FU = 1 tonne textile waste)*

Material	Indicator	Impact	LCA Location	Source
Cotton	Aquatic Eutrophication Potential	0 kg NO_3^-	Turkey	(Baydar et al., 2015)
	Global Warming Potential	2,000 kg CO_2e	Turkey	(Baydar et al., 2015)
	Terrestrial Eutrophication Potential	50 kg NO_3^-	Turkey	(Baydar et al., 2015)

Table 16 *Impacts of incineration with energy recovery (FU = 1 tonne textile waste)*

Material	Indicator	Impact	LCA Location	Source
Cotton	Global Warming Potential	-820 kg CO_2e	China	(Luo et al., 2022)
		-600 kg CO_2e	Netherlands	(van der Velden et al., 2014)
Poly-Cotton Blend	Global Warming Potential	-1,040 kg CO_2e	Denmark	(Koligkioni et al., 2018)
		230 kg CO_2e	Sweden	(Zamani et al., 2015)

Table 17 *Impacts of mechanical recycling (FU = 1 tonne textile waste)*

Material	Indicator	Impact	LCA Location	Source
Cotton	Acidification Potential	-14.76 kg SO_2e	Australia	(Moazzem et al., 2021b)
	Agricultural Land Occupation	-3,671.85 m^2a	Australia	(Moazzem et al., 2021b)
	Global Warming Potential	-1,502.43 kg CO_2e	Australia	(Moazzem et al., 2021b)
	Water Depletion	-860.62 m^3	Australia	(Moazzem et al., 2021b)
Nylon	Energy Consumption	985.48 MJ	United States	(Sim & Prabhu, 2018)
	Global Warming Potential	192.47 kg CO_2e	United States	(Sim & Prabhu, 2018)

Table 18 *Impacts of chemical recycling (FU = 1 tonne textile waste)*

Material	Indicator	Impact	LCA Location	Source
Polyester	Acidification Potential	0.16 kg SO_2e	Australia	(Moazzem et al., 2021b)
	Agricultural Land Occupation	1.27 m^2a	Australia	(Moazzem et al., 2021b)
	Global Warming Potential	-267.73 kg CO_2e	Australia	(Moazzem et al., 2021b)
		-900 kg CO_2e	Sweden	(Zamani et al., 2015)
	Water Depletion	0.29 m^3	Australia	(Moazzem et al., 2021b)
Poly-Cotton Blend	Global Warming Potential	-5,500 kg CO_2e	Sweden	(Zamani et al., 2015)

Disposal Fate Modeling

Model of Vietnam's Energy Grid

The impact values of the Vietnamese energy grid are included in Table 19. All values are based on the grid breakdown from 2021 provided in Table 8.

Table 19 *Vietnamese energy grid impacts (FU = 1 gigawatt hour (GWh))*

Impact Category	Impact Value
Acidification Potential	0.0251 kg SO_2 eq.
Eutrophication Potential	0.0025 kg N eq.
Global Warming Potential	2.9227 kg CO_2 eq.
Photochemical Ozone Creation Potential	0.2240 kg O_3 eq.

Landfill Emissions Simulation

Cotton was estimated to have an impact of 6.63 tonnes of carbon dioxide equivalent. This result assumes complete decomposition of its full carbon content into 50% carbon dioxide and 50% as methane (see Table 20; US EPA, 2016a). Synthetic materials, like nylon and polyester, are considered inert in landfills due to their comparatively large decomposition timescales and do not have associated emissions in this model. It is important to note that synthetics can have an impact outside of direct emissions when landfilled.

Table 20 *Decomposition emissions (FU = 1 tonne of specified textile material)*

Material	Carbon Content	CH_4 emissions	CO_2 emissions	Total CO_2e
Cotton	0.445 tonnes	0.2225 tonnes	0.2225 tonnes	6.6305 tonnes
Nylon	0.637 tonnes	N/A (Inert)	N/A (Inert)	N/A (Inert)
Polyester	0.625 tonnes	N/A (Inert)	N/A (Inert)	N/A (Inert)

Incineration Analysis

Incineration without waste-to-energy resulted in 1.32 kg of SO_2 equivalent, 0.09 kg of nitrogen equivalent (N eq.), 1,737.07 kg of carbon dioxide equivalent, and 40.6 kg of ozone equivalent (O_3 eq.). See Table 21.

Table 21 *Incineration impacts (FU = 1 tonne textile waste)*

Impact Category	Impact Value
Acidification Potential	1.32 kg SO_2 eq.
Eutrophication Potential	0.09 kg N eq.
Global Warming Potential	1,737.07 kg CO_2 eq.
Photochemical Ozone Creation Potential	40.6 kg O_3 eq.

Discussion

This project aimed to determine the environmental and public health impacts of pre-consumer cut-and-sew textile waste. The team spent twelve months analyzing academic literature, LCAs, and industry research to identify and compare these impacts. In this section, the team discussed the project's conclusions.

Cut-and-Sew Waste Quantification

The results of this study indicate Tier 1 Facilities in Vietnam within Patagonia's supply chain waste approximately 18% of total fabric, around 640 tonnes. Polyester accounts for the most significant portion of this waste, followed by nylon, cotton, and blends (Table 10). This distribution of material wasted is representative of the material utilized in the cut-and-sew process of Patagonia products made in Vietnam.

The volume of pre-consumer waste is influenced by garment type, pattern style, and size. Technical garments require pattern makers to increase the size of each panel on the garment to minimize seams enabling higher performance, such as better waterproofing. This results in more waste than casual garments because fewer pattern pieces fit onto a marker. Patterned fabric can also produce more waste because they are challenging to match along seams. Companies that produce technical outdoor apparel prioritize garment performance, so their design patterns and concepts may have a higher pre-consumer waste profile.

Within the literature, the accepted value for industry pre-consumer waste is 10–15% of the total necessary fabric (Rissanen, 2005). This value is lower than the team's average estimation of 18%, which may be due to the 2005 value being out-of-date or an underestimation. As previously mentioned, pre-consumer waste metrics are not frequently tracked by brands, so averages within literature are not confidently established.

Barriers to Pre-Consumer Waste Measurement

Apparel brands do not commonly measure or disclose pre-consumer textile waste. The barriers preventing industry-wide measurement include:

1. **Supply chain structure**: The complexity of an apparel brand's supply chain is the most significant barrier. Brands do not typically own the garment factories that produce their inventory, resulting in highly complex supply chains with multiple tiers of suppliers involved in the production process. Suppliers and brands often operate across multiple geographical locations and legal jurisdictions, making it difficult for brands to obtain accurate data from suppliers.

2. **Traceability**: Brands frequently lack visibility beyond Tier 1 suppliers, work with suppliers who do not disclose their waste practices, or have suppliers who experience challenges with collecting primary data. Garment factories can obtain data on their waste through

waste hauler bills, as some companies charge by weight. However, factories may have additional waste, like hardware or packaging, that adds to the weight of their waste.

3. **Confidentiality and competition**: Lastly, competition and publicity concerns impede apparel brands from voluntarily publishing data. Some companies may hesitate to disclose information out of fear of negative publicity or putting themselves at a competitive disadvantage.

One way to address these challenges is to implement waste-tracking technologies. However, these technologies can be expensive and factories may lack the resources to invest in them. By disclosing some of their pre-consumer waste data for the first time, Patagonia aims to inspire other brands to push past these barriers and begin to measure and manage this hidden problem.

Impact Analysis

Regional Assessment

The team researched the waste management infrastructure and policy in Vietnam to ensure the impact assessment results were contextualized for the recommendation. This research is detailed in the *Regional Context in Vietnam* section.

Vietnam's energy grid mix is essential to determine the impacts of any energy-intensive activities. The grid mix primarily depends on fossil fuels, predominantly coal (49%) and oil (24%) (IEA, 2021). Only 10% of the grid is renewable, and the remaining energy comes from biofuels, waste, or natural gas (Table 8).

Third-party waste haulers collect textile waste generated at Tier 1 apparel factories in Vietnam. After transport to a designated sorting location, the waste undergoes manual separation. This process separates fabric from other materials and categorizes textiles by fiber type. Following sorting, the waste is transported to disposal or recycling, as shown in Figure 3 (GCIC, 2022). The allocation percentages to each disposal pathway remain unclear. Additional regional considerations for these disposal methods are included in subsequent sections.

Impacts of Landfilling

The environmental impacts of landfills depend on the type and volume of waste, the facility's age, regional conditions (e.g., climate), and the processing technology used. When improperly managed, sanitary landfills handling typical MSW have the potential to release emissions into the air, soil, and nearby waterways. Unsanitary landfills have more significant impacts than sanitary landfills because of the lack of pollution control. Due to the limited research on the impacts of textiles in landfill, the team expanded research to include the impacts of MSW, but must note that waste fabrics are chemically distinct from and may be much more inert than most types of MSW. Impacts on the natural environment from MSW in landfills can include hazardous leachates, acidification, air pollutants, greenhouse gasses such as carbon dioxide and methane, contamination from heavy metals, eutrophication, odor pollution, and degradation of freshwater resources (Table 11). These environmental impacts can also have adverse health effects within adjacent communities. The impacts on human health associated with MSW in landfills include respiratory illnesses, such as asthma, caused by air pollution, carcinogens, odor pollution, and water pollution (Table 12).

Limited research on the impacts of textile waste in landfills is available, but the team was able to find three LCAs that included the end-of-life impacts of nylon, polyester, poly-cotton, and cotton when disposed of in landfills. Two studies in Australia concluded that nylon, polyester, and cotton impacted global warming potential, acidification potential, agricultural land occupation, and water depletion, with cotton resulting in the most significant global warming potential (Table 14). When cotton degrades under anaerobic landfill conditions methane is released (Azcona et al., 2023). In these LCAs, the methane is not captured for energy generation (Table 14). In contrast, another study in Australia found that the poly-cotton blended fabric resulted in reduced global warming potential because of an electricity credit from landfill methane gas captured for energy generation in their scenario (Table 14).

In Vietnam, landfills are the primary endpoint of disposal. Only 17–20% of these landfills are sanitary with a barrier between waste and the surrounding environment (Duc Luong et al., 2013; MONRE, 2004; MONRE, 2020). This is important to consider when comparing disposal in Vietnam to disposal in countries with more advanced landfill infrastructure.

Impacts of Incineration

The magnitude of environmental and health impacts from incinerators depend on the type of incineration facility. Incinerators without emission controls have the highest health and environmental impacts, whereas those with emission controls have a more significant greenhouse gas impact compared to incinerators with waste-to-energy recovery. In studies about MSW, the environmental impacts of incineration were acidification, air pollution, climate change contribution, and heavy metal pollution. The health impacts of MSW incinerators were air pollution, climate change, and respiratory illness.

Only a handful of material-specific public LCAs were identified from Turkey, China, Netherlands, Denmark, and Sweden. These data highlight that cotton incineration without energy recovery in Turkey resulted in 2,000 kg CO_2e per tonne of fabric. In comparison, incineration of cotton with energy recovery in China and the Netherlands resulted in -820 kg CO_2e and -600 kg CO_2e, respectively. These results indicate that incineration without energy recovery has higher impacts than WTE incineration because of avoided energy production. The differences between the results of incineration with energy recovery in China and the Netherlands can likely be attributed to differences in regional energy grids. The WTE incineration of poly-cotton blend fabric had a range of GWP impact from -1,040 kg CO_2e in Denmark to 230 kg CO_2e in Sweden. Both studies allocate credits for the avoided energy production, but the difference is likely due to the differing levels of fossil fuels in the grids that the energy is displacing. In Denmark, 54.1% of the energy grid supply is from fossil fuels (IEA, 2022a). In contrast, Sweden has an energy grid supply where 23.3% is from fossil fuels (IEA, 2022b). Displacing energy from fossil fuel sources will result in a more significant reduction in impacts due to avoiding GHGs. LCAs on the incineration of nylon or polyester were not found. This research concluded that from an LCA perspective, incineration with waste-to-energy recovery has lower impacts than incineration without energy recovery because energy production is credited towards reducing GWP. It is essential to recognize that there are still emissions from WTE incineration, and local communities may not experience the benefit of avoided energy production if energy is not generated in their area.

Currently, only 13% of MSW in Vietnam is incinerated. Out of the total 381 MSW incinerators in the country, 88 facilities (23%) do not have an exhaust gas treatment system or do not meet policy standards (MONRE, 2020). Waste-to-energy facilities are rare in Vietnam due to the high cost of investment, operating costs, and technical requirements. Additionally, due to the high moisture content in the MSW composition in Vietnam, incinerators must expend extra energy in order to evaporate off the moisture in the waste, impeding incinerators from running at maximum efficiency (Duc Luong et al., 2013; MONRE, 2020). Most waste that is incinerated in Vietnam is not combusted in a facility with energy recovery or emissions controls (MONRE, 2020). As a result, textile waste incinerated in this region has greater environmental and health impacts compared to waste incinerated in a region with a higher proportion of regulated or WTE incinerators.

Impacts of Recycling

The team's analyses show that recycling has great environmental advantages compared to any other mode of waste disposal. Although this result is not surprising, it highlights the need to greatly increase industry efforts to recycle fabric waste. First and foremost, recycling avoids much of the harms that would otherwise occur during fiber and fabric production, such as from growing cotton and turning it into a usable fabric.

This project analyzed the impacts of two types of textile recycling: mechanical and chemical. Both forms of textile recycling involve recovering textiles to be reprocessed into a new format or product. One disadvantage of textile recycling is the quality degradation that occurs when the original textile is broken down. Recycled content is typically blended with virgin fibers to create a usable output.

Mechanical recycling refers to the physical breakdown of fiber structure into a format small enough to be re-spun or re-extruded into new fiber. The team found little research on the impacts of this disposal method. Like the other disposal methods, mechanical recycling requires energy that can produce GHG emissions. The team identified a single LCA study with end-of-life impacts of cotton mechanical recycling. In this study, acidification potential, agricultural land occupation, global warming potential, and water depletion values indicated an environmental benefit when cotton was recycled. It should be noted that this positive effect can be attributed to the avoided primary production of cotton fiber, which offset the energy required to break down and re-spin the cotton in the mechanical process. In Vietnam, two types of mechanical recycling occur with textile waste: polyester scraps pelletized or shredded into fibers for product reuse and cotton scraps shredded into fiber for yarn production (GCIC, 2022).

The team could not determine the impacts of these processes in Vietnam from academic research. It should be noted that the country's energy grid mix is three-fourths fossil-fuel-based. With reliance on fossil fuels, any energy-intensive activities will impact the environment through greenhouse gas emissions.

Chemical recycling refers to breaking existing materials or polymers into chemical components or monomers for new applications (Textile Exchange, 2021). The chemical solvents and catalysts used in chemical recycling can be highly toxic to humans and the natural environment (Table 13). These processes must occur in a regulated laboratory or manufacturing environment to ensure the chemicals are not mishandled or discharged into the surrounding environment. Some chemical recycling processes require high temperatures, high pressure, and large amounts of water (Table 1 & 2). Each of these requirements can have environmental implications depending on the region in which they occur. The team identified two LCA studies with end-of-life impacts on polyester and poly-cotton chemical recycling. These studies indicated that recycling efforts can reduce the impact of original fabric production on the environment. This reduction can be attributed to the avoided primary production of fiber, which offsets the energy required to break down and re-spin the fiber during chemical recycling. The team could not identify any industrial-scale chemical textile recycling facilities in Vietnam.

Disposal Method Tradeoffs

The project set out to research the impact of textile waste in a community and whether it varies by region. While the project could not find Vietnam-specific environmental and health impact data, the research highlighted that impacts differ per region. This variation underscores the importance of examining the manufacturing facilities' regional context. In addition to regional context, each disposal method varies based on technology, regulatory oversight, and waste volume. The environmental and public health impacts of unsanitary landfills are more significant than those of sanitary landfills. As stated earlier, 80% of landfills in Vietnam are unsanitary, meaning that landfilled textiles have a more significant impact in Vietnam than in a region with primarily sanitary landfills.

Similarly, the impacts of incineration are reduced if the facility has emissions controls or energy recovery compared to an outdated or standard incinerator. Since 23% of the 381 MSW incinerators in the country do not have an exhaust gas treatment system and only a handful of WTE facilities, incineration in Vietnam has a more significant impact than regions with predominantly WTE or regulated incinerators. While there is minimal research on the impacts of mechanical and chemical recycling, the drawbacks are energy usage for mechanical recycling and chemical usage for chemical recycling. If the recycled material avoids the primary production of textiles, then this would be the disposal method with the lowest impact. Due to the degradation of fiber quality in the recycling process and the requirement of some virgin materials, further research is needed to confirm the magnitude of primary production impacts avoided through recycling materials.

Limitations

LCA Limitations

LCA results are a functional tool for estimating the impacts of a product or process. However, several limitations must be considered. Each LCA must explore a particular scenario and make many assumptions, making comparison of results from one study to another challenging without adjusting data inputs. The results can be heavily influenced by the system boundaries delineated and processes that may have been excluded or simplified. Additionally, LCAs often do not include enough specificity within results to adjust the specific data inputs and yield more applicable results.

The Sphera database provides information regarding more developed regions like Europe and the United States. This supports our finding that there is a lack of data for Vietnam. This directly impacts the comparability of our results because different regions have unique end-of-life options. For example, approximately 20% of incinerators in Vietnam do not meet the required exhaust gas treatment standards, and only a few have energy capture technology. However, incinerators in Europe and the U.S. must meet higher standards and are more likely to have energy capture in place. By capturing energy from landfill and incineration processes, the impact of these disposal methods can be reduced as they eliminate the need for energy from other sources. Due to these regional nuances, environmental and health impacts of landfill and incineration may be underestimated in an LCA if Sphera's database is used.

LCA results often indicate that landfilling synthetic materials like polyester and nylon has little impact since they do not decompose or emit greenhouse gasses. However, concerns about microplastic pollution and water quality caused by synthetic materials are not accounted for in an LCA (Wojnowska-Baryła et al., 2022). In addition, an LCA does not capture social impacts, such as the displacement of communities due to landfill expansion (Yang et al., 2020). Although LCAs are a valuable tool in assessing and quantifying environmental impacts, it is essential to acknowledge their limitations when using the results to make decisions.

Data Availability

The project faced data gaps related to the impacts of textile waste in different geographic regions, particularly in Vietnam, where information on waste management after leaving Tier 1 cut-and-sew facilities was lacking, hindering a comprehensive assessment of textile waste impacts. Additionally, there was a lack of specific research on the environmental and health impacts of textile waste in landfills, incinerators, and recycling facilities, with most studies focusing on general MSW. Despite the target material types comprising a significant portion of the global fiber market, there was limited academic research or LCAs on the end-of-life impacts of these materials and disposal types. These gaps were attributed to industry-wide challenges and highlighted the need for increased transparency in the apparel industry.

Region-Specific Data

The team set out to compile academic research on the impacts of textile waste in Vietnam. During this phase, the team found that most end-of-life textile research is currently conducted in Europe and Australia. The team researched waste flows in Vietnam's apparel manufacturing sector to address this gap. By analyzing academic literature and the supplemental survey results, the team identified that waste from Tier 1 cut-and-sew facilities is handled by third-party waste contractors (Appendix C). While survey results identified names of some contractors, no public data on the fate of the waste was available beyond this point. Existing estimates suggest that 2–7% of Vietnam's MSW is textile-based (Duc Luong et al., 2013; MONRE, 2020). The lack of information on where waste goes after leaving factories, whether for disposal or reuse, hinders a comprehensive assessment of textile waste impacts in Vietnam.

Impacts of Textile Waste Management Data

The team initially planned to research textiles to better understand their environmental and health impacts in landfills, incinerators, and recycling facilities. However, there is little academic research on the impact of textile waste. Researchers widely study the impacts of textiles using LCAs; however, most LCAs only analyze the cradle-to-gate phase, which includes an analysis of impacts from resource extraction to production (van der Velden et al, 2014). Finding LCAs that included a cradle-to-grave analysis with end-of-life impacts was challenging. The team reviewed 58 LCAs on textile impacts but only found 12 that included end-of-life impacts for cotton, polyester, or nylon. These findings highlight the need for further research and LCA studies that include end-of-life impacts.

Outside of LCAs, only four academic studies directly linked textiles to the end-of-life impacts of waste management methods. Two of those studies researched the impacts of general textile waste, including post-consumer waste. Despite cotton, polyester, and nylon comprising 80% of the global fiber market, academic research on the end-of-life impacts of polyester or nylon was not found, and only two studies linked end-of-life impacts to cotton (Textile Exchange, 2021).

The textile waste impact data gaps are attributed to the industry's overall lack of transparency, which stems from opaque supply chains, proprietary information protection, lack of data collection resources, and inconsistent use of terms. As sustainability regulations increase, transparency will likely increase, but it may take time before publicly available data are available. Publicly available databases are needed in the apparel industry to improve supply chain data discoverability, accessibility, interoperability, and reusability. One effort to increase apparel supply chain transparency is Worldly (formerly Higg Index), a platform developed by the nonprofit Cascale (formerly Sustainable Apparel Coalition). Over 40,000 brands, retailers, and manufacturers use the platform to collect data. This project initially set out to use data in Worldly but found challenges with inconsistent use of terms. Without high-quality data, concluding the environmental and health impacts of the disposal options for pre-consumer waste is challenging.

Summary of Key Findings

1. **Barriers to Measuring Pre-Consumer Textile Waste**
   Supply chain structure, lack of waste traceability, and competition concerns make it difficult for the apparel industry to quantify this waste stream accurately.

2. **Location Matters for Waste Impact**
   The impact of waste on the environment and public health varies widely depending on the location. Factors such as energy sources, waste management infrastructure, technical regulation, monitoring, oversight, and landscape all play a role in determining the severity of the impacts.

3. **Vietnam's Waste Management Challenges**
   Vietnam faces challenges in managing its waste due to the lack of essential pollution control technology in many landfills and incinerators. Therefore, until these systems are updated, it is essential to prioritize waste prevention, recycling, and reuse.

4. **Recycling is Favorable for Mitigating Impact**
   Recycling has environmental advantages over other disposal methods. Recycling avoids much of the environmental harm during fiber and fabric production.

Recommendations

The final objective of this project was to provide a recommendation to minimize impact based on Vietnam's existing infrastructure, environmental policy, regional challenges, and opportunities. Given the discussion above, the team has identified five key areas to address the environmental and public health impacts of textile waste in Vietnam over the next two to three years.

Legislative Advocacy

Around the globe, current and proposed legislation aims to regulate companies' tracking, measurement, and disclosure of their environmental impacts. The team set out to identify which policies, if any, require companies to measure their pre-consumer textile waste for external reporting. No regulations require tracking this waste at a facility or brand level. However, two pieces of legislation in the European Union (EU) are important to monitor for their impact on transparency in the apparel supply chain: the Corporate Sustainability Reporting Directive (CSRD) and the Eco-design for Sustainable Products Regulation (ESPR).

The CSRD went into effect in 2023 and requires detailed reporting requirements for public and private companies, like Patagonia, that have business in the EU. It includes a reporting standard that mandates reporting on resource consumption, waste generation, circular design, and recovery of products and materials. Companies are encouraged to assess their circularity performance across the entire value chain. Companies must report quantitative indicators such as targets and circular performance across resource inflows and outflows. Reporting includes waste management and its overall contribution to circularity through design for recovery and the recirculation of products and materials (Matinetti, 2023). Companies must report "actions taken to prevent waste generation in the upstream and downstream value chain" (KPMG, 2023). However, it is unclear if companies must report on waste generated in their supply chain. Patagonia could help lead the way by reporting on pre-consumer textile waste amounts and impacts for CSRD and other public disclosures. By publicizing pre-consumer waste, Patagonia might help push the industry to take action on this issue and invest in textile recycling.

The ESPR legislation, published in March 2022, aims to enhance products' circularity and energy efficiency. It proposes that by 2030, all textiles sold within or outside of the EU must possess a mandatory Digital Product Passport (DPP) (Circular, 2022; European Commission, n.d.). The DPP is intended to standardize information sharing throughout the supply chain. The passport will include various data points, such as information on the product's material, supply chain, and circularity, accessible through a QR code, chip, or tag. Recycling and repair instructions, supplier name and location, and information on harmful substances are examples of data points that will be included (Trace4Value, n.d.). The European Commission aims to approve ESPR in the first six months of 2024. They recognize the importance of developing the DPP through an open dialogue with international partners to eliminate trade barriers for sustainable products and lower costs associated with sustainable investments and compliance (European Commission, n.d.).

It is unclear if pre-consumer textile waste will be tracked under ESPR. However, if finalized, ESPR will require companies to strengthen traceability in their supply chain. The team recommends that the apparel industry advocates for pre-consumer textile waste to be included under the circularity information in the DPP. This regulation can potentially enable investment into comprehensive tracking and traceability in the apparel supply chain.

Apparel Industry Collaboration

Because apparel brands share garment factories, collaboration between brands within the same facilities can support streamlining processes and fostering innovation, particularly for sustainability and social responsibility. Brands can begin fostering inter-facility partnerships by setting up a communication channel. Once brands have built relationships with one another, they can encourage a culture of collaboration by working together to reduce the impacts of the facility. Brands can collaborate on supplier development programs within the facilities to initiate fabric-efficiency workshops, sustainability training, and technology adoption. Lastly, brands can cooperate on solutions for scrap waste on a facility-by-facility basis based on local opportunities and restrictions. The ultimate goal of these brand collaborations is to form partnerships that influence facilities to adopt more sustainable solutions for cut-and-sew waste.

To influence facilities, brands could consider leveraging collaboration through NGOs, industry associations, public-private partnerships, and platforms to advocate for change collectively. NGOs, such as the Ellen MacArthur Foundation, are building a network of brands collaborating to scale textile recycling and advocate for measurement and reporting on progress towards circular economy outcomes (Ellen MacArthur Foundation, 2024). Platforms like Reverse Resources connect textile waste producers with waste handlers and recyclers. Through its Innovation Platform, Fashion for Good has created an ecosystem connecting brands, retailers, and manufacturers with textile recyclers and funders.

Scaling Recycling Technologies

Chemical recycling technologies are being developed in academic and industry settings around the world. Birla Cellulose, Lenzing REFIBRA, Evernu Nucycl, and Ioncell are fibers produced from chemically recycled cotton textile waste. Jeplan's technology recycles polyester clothing into pellets to create virgin-quality polyester. Worn Again Technologies, Hong Kong Research Institute of Textile and Apparel's "The Green Machine," Blocktexx, and Circ are companies currently developing methods to chemically separate and recycle poly-cotton blends. These innovations represent a fraction of chemical recycling technologies on the market. Each one can potentially divert textile waste from landfills and incineration facilities. Most textile-to-textile chemical recycling technologies are nascent and currently unable to scale on a commercial level. Cost is the most significant barrier to scaling these technologies. The team recommends that Patagonia and the broader apparel industry support the research and development of chemical recycling technologies to create additional opportunities for the circularity of textile waste.

Waste Management Strategies

It is essential to understand Vietnam's import and export regulations to provide a recommendation on how to handle cut-and-sew waste. Most goods imported or exported in Vietnam are subject to their respective duties, a form of taxes collected by customs authorities based on the value of goods. Given current regulations, two import and export duty exemptions for fabrics are possible in Vietnam's garment factories: goods that are temporarily imported for re-export or imported for processing for foreign partners and then exported (Dezan Shira & Associates, 2019). Based on the team's understanding of these regulations, garment factories can import fabrics duty-free into Vietnam only if the materials are consumed to produce garments that are subsequently exported. Any fabric not used in the garment is subject to import duties if it remains in the country as a good. Based on information from industry interviews, scrap waste is destroyed through disposal to avoid duties of around 40%. This policy landscape is similar to that of the United States and Italy, which allow tax write-offs for unsold inventory that is destroyed (Napier & Sanguineti, 2018). In Vietnam, one way to secure tax exemptions without disposal is through the use of agglomerators that turn fabric into a new form. Using agglomerators is challenging because there are very few in the country, and the resulting product needs to be a feedstock for another product. Based on these policies, the project did not consider waste export as a recommendation.

The suggested strategy for the next 1–3 years is to prioritize sorting materials to support faster adoption of available recycling or reuse solutions. Manufacturing sites generate mixed waste with both recyclable and non-recyclable fabric scraps, indicating the need for worker training and improved handling practices to maximize recyclable waste volumes. Fabric sorting at the factory level can significantly reduce recycler costs, potentially saving 10–30% of production costs (GCIC, 2022). However, many manufacturers currently do not sort fabric scraps at the source, which decreases recycling efficiency. Real-time sensors are recommended to identify textile materials accurately. Standardized measurement protocols and capacity development for fabric waste sorting and segregation, especially at the factory level, are also crucial.

Future Research

The investigation into the impacts of pre-consumer textile waste revealed significant data gaps, especially in Vietnam. To advance knowledge of the environmental and health impacts of textile waste, the following areas are recommended for future research:

1. **Analysis of impacts of textile waste across disposal methods and geographies**
   NGOs and university researchers are encouraged to investigate the environmental and health impacts of textile waste in landfills, incinerators, and recycling facilities. The team recommends this research go beyond general MSW studies and delve into unique characteristics and consequences of textile waste disposal. Analysis of pollution levels,

leachate, and emissions from each disposal method can fill the environmental and health data gaps associated with each approach. Ideally, these studies would be conducted worldwide to assess the region-specific impacts further and compare variations.

2. **Quantification of additional sources of pre-consumer waste**
   This research focused on cut-and-sew facility waste, which is not the only pre-consumer textile waste produced in the apparel production process. Future research can study waste from damaged garments, unsold garments, clothing samples, textile swatches, and sampling yardage. It is estimated that more than 25% of produced garments go unsold (McKinsey, 2021). Aside from cut-and-sew scraps, sampling yardage likely has a higher waste contribution than the other categories because of minimum order requirements when purchasing fabric. One nonprofit, FabScrap, aims to increase the reuse of this waste by collecting and reselling sampling yardage waste in New York City and Philadelphia. Since this study did not measure the other types of pre-consumer waste, Patagonia can pursue further research that measures all forms of pre-consumer waste.

3. **Uncover sources of microplastics from pre-consumer textile waste**
   Future research should also focus on the impacts of textile waste on microfiber and microplastic pollution. Approximately 35% of the microplastics in the ocean are microfibers released from synthetic textiles (Boucher & Friot, 2017). Microplastic releases into waterways from synthetic textiles primarily come from machine washing in the consumer use phase (Boucher & Friot, 2017). However, microplastics have been documented in landfill leachate, and some of this pollution may come from pre-consumer textile waste (Kabir et al., 2023). Microplastics can transport harmful pollutants and bioaccumulate in organisms and our food systems. Additionally, research should focus on the links between textile waste, microplastic pollution, and impacts to human health.

Our team hopes that the findings presented in this report will raise awareness about pre-consumer textile waste and the impacts of current disposal methods. Our interdisciplinary approach combined environmental science, engineering, policy analysis, and industry collaboration. Such an approach seems essential for mitigating global environmental and health risks associated with textile waste. Our team encourages further research on end-of-life impacts and pre-consumer textile waste transparency by highlighting the data gaps. Addressing these research areas can fill critical data gaps, enhance understanding of textile waste impacts, and develop evidence-based strategies for sustainable waste management in the apparel industry.

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Appendix A - Glossary

Term	Definition	Source
Aquatic Eutrophication Potential (AEP)	In LCA, AEP is the potential impact of a product or activity on an increase in aquatic plant growth attributable to nutrients left by over-fertilization of water and soil, such as nitrogen and phosphorus.	(Čuček et al., 2015)
Agricultural Land Occupation (ALO)	The area of land needed to produce the chosen functional unit (i.e. 1 tonne of textile).	(Romano et al., 2021)
Acidification Potential (AP)	Measure of the compounds that are precursors to acid rain. These include sulfur dioxide (SO2), nitrogen oxides (NOx), nitrogen monoxide (NO), nitrogen dioxide (N2O), and other various substances.	(Moazzem et al., 2021a)
carbon dioxide equivalent (CO_2e)	The number of tonnes of CO_2 emissions with the same global warming potential as one metric ton of another greenhouse gas.	(US EPA, 2015)
carcinogenicity	A carcinogen is a chemical substance or a mixture of chemical substances that induces cancer or increases its incidence.	(SCHC-OSHA Alliance, 2017)
circular economy	Maximizing the use and value of products, materials, and resources by keeping them in circulation for as long as possible through strategies like reuse, recycling, and repurposing, while minimizing waste generation.	(Maitre-Ekern, 2021)
clothing samples	Garments produced in the design and clothing production process to test a new design, fabric, or sewing pattern.	(McKinsey, 2021)

cradle-to-gate	Analysis from resource extraction (cradle) to factory gate before being sent to consumers (gate); it excludes the use and the disposal phases.	(Čuček et al., 2015)
cradle-to-grave	Analysis of the system's whole life cycle from the extraction (cradle) and processing of resources through manufacturing, usage, and maintenance to recycling or disposal (grave), including all transportation and distribution steps.	(Čuček et al., 2015)
damaged garments	Unused textiles that are either physically damaged or have a defect like a color or print error.	(McKinsey, 2021)
Extended Producer Responsibility (EPR)	A policy approach that holds producers responsible for product management through the product's lifecycle.	(Maitre-Ekern, 2021)
flue gas	The gas that emanates from combustion plants. It contains the reaction products of fuel and combustion air and residual substances such as particulate matter (dust), sulfur oxides, nitrogen oxides, and carbon monoxide.	(ScienceDirect Topics, n.d.)
functional unit (FU)	A quantitative description of the function or service for which the assessment is performed, and the basis of determining the reference flow of the product that scales the data collection.	(Čuček et al., 2015)

germ cell mutagenicity	A germ cell mutagen is a chemical that may cause mutations in the germ cells of humans that can be transmitted to the progeny. A mutation is defined as a permanent change in the amount or structure of the genetic material in a cell.	(SCHC-OSHA Alliance, 2017)
Global Warming Potential (GWP)	The measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2).	(US EPA, 2016)
landfill leachate	When liquid, usually rainwater, comes in contact with buried wastes in a landfill, it leaches, or draws out, chemicals or constituents from those wastes.	(US EPA, 2016)
life cycle assessment (LCA)	A structured, comprehensive, internationally standardized tool for quantifying those emissions, resource consumptions, and environmental and health impacts associated with processes, products, or activities.	(Čuček et al., 2015)
man made cellulosic fiber (MMCF)	Regenerated fibers are usually made from the dissolved wood pulp or “cellulose” of trees. Viscose, lyocell, and modal are all kinds of manmade cellulosics.	(Textile Exchange, 2021)
microplastics	Extremely small pieces of plastic, manufactured as such or resulting from the disposal and breakdown of plastic products and waste.	(Oxford English Dictionary, n.d.)

sampling yardage	Surplus fabric waste leftover from the factory or designer's process of making garment samples.	(McKinsey, 2021)
Terrestrial Eutrophication Potential (TEP)	In LCA, TEP is the potential impact of a product or activity on terrestrial ecosystems by evaluating its contribution to nutrient enrichment and subsequent ecological disturbances.	(Čuček et al., 2015)
textile swatches	Small pieces of fabric that designers and facilities use when choosing fabrics to make samples.	(McKinsey, 2021)
unsold garments	Finished goods not sold to consumers or brands are considered.	(McKinsey, 2021)

Appendix B - Supplemental Tables and Figures

Table B-1 *Specific impacts of landfill on the natural environment*

Impact Category	Impact Description	Material	Location	Source
Acidification	Sulphates	MSW	India	Paul et al. 2019
Air Pollution	Air Pollution	MSW	Assorted	Siddiqua et al. 2022
Climate Change	Methane (CH_4), Nitrous dioxide (NO_2)	MSW	South Africa	Njoku et al. 2019
Heavy Metals	Copper (Cu), Iron (Fe), Lead (Pb)	MSW	India	Paul et al. 2019
Eutrophication	Phosphates	MSW	India	Paul et al. 2019
Odor pollution	Hydrogen sulfide (H_2S)	MSW	China	Wu et al. 2018
Water Pollution	Underground water pollution	MSW	Assorted	Siddiqua et al. 2022

Table B-2 *Specific impacts of incineration on the natural environment*

Impact Category	Impact Description	Material	Location	Source
Air Pollution	Fly ash, Flue gas: CO_2, CO, CH_4, NO_x, SO_2, H_2S, HCl, HF, PM 10, Hg, Pb, Cr, Ni, Slag	MSW	Tibet	Dan et al. 2022
Air Pollution	Dry flue gas, Nitrous oxides (NO_x)	MSW	China, EU, US, Japan, South Korea, Taiwan	Lu et al. 2017.
	Nitrous oxides (NO_x), Particulate matter (PM)	MSW	Europe	Dong et al. 2018
	Dirt debris	MSW	Sri Lanka	Dilshani et al. 2019
Carcinogens	Flue gas: PCDDs and PCDFs	MSW	Tibet	Dan et al. 2022
	Dioxins	MSW	China, EU, US, Japan, South Korea, Taiwan	Lu et al. 2017.
	PCDDs and PCDFs	MSW	Europe	Dong et al. 2018
	Dioxins	MSW	Sri Lanka	Dilshani et al. 2019

Table B-3 *Specific impacts of mechanical recycling on the natural environment*

Impact Category	Impact Description	Material	Location	Source
Acidification	Sulfur dioxide equivalent (SO_2 eq.)	Cotton	Spain	Esteve-Turrillas and de la Guardia 2017
Air Pollution	non-methane volatile organic compounds (NMVOC equivalent)	MSW	Germany	Harish et al. 2021
Climate Change	Carbon dioxide equivalent (CO_2e)	Cotton	Spain	Esteve-Turrillas and de la Guardia 2017
	Carbon dioxide equivalent (CO_2e)	MSW	Germany	Harish et al. 2021
Eutrophication	Phosphates	Cotton	Spain	Esteve-Turrillas and de la Guardia 2017

Table B-4 *Specific impacts of landfill on human health*

Impact Category	Impact Description	Material	Location	Source
Air Pollution	Air Pollution	MSW	Assorted	Siddiqua et al. 2022
Climate Change	Methane (CH_4), Nitrous dioxide (NO_2)	MSW	South Africa	Njoku et al. 2019
Carcinogens	Dioxins: PCDDs, PCDFs, and PAHs	MSW	South Africa	Njoku et al. 2019
	Trichloropropane, Naphthalene, Trimethylbenzene	MSW	China	Wu et al. 2018
Eye Irritation	Eye irritation	MSW	South Africa	Njoku et al. 2019
Odor Pollution	Odor pollution	MSW	Assorted	Siddiqua et al. 2022
	Hydrogen sulfide (H_2S)	MSW	China	Wu et al. 2018
Respiratory Illness	Flu, Respiratory irritation	MSW	South Africa	Njoku et al. 2019
Water Pollution	Underground water pollution	MSW	Assorted	Siddiqua et al. 2022

Table B-5 *Specific impacts of incineration on human health*

Impact Category	Impact Description	Material	Location	Source
Air Pollution	Fly ash, Flue gas: CO_2, CO, CH_4, NO_x, SO_2, H_2S, HCl, HF, PM 10, Hg, Pb, Cr, Ni, Slag	MSW	Tibet	Dan et al. 2022
Air Pollution	Dry flue gas, Nitrous oxides (NO_x)	MSW	China, EU, US, Japan, South Korea, Taiwan	Lu et al. 2017.
	Nitrous oxides (NO_x), Particulate matter (PM)	MSW	Europe	Dong et al. 2018
	Dirt debris	MSW	Sri Lanka	Dilshani et al. 2019
Carcinogens	Flue gas: PCDDs and PCDFs	MSW	Tibet	Dan et al. 2022
	Dioxins	MSW	China, EU, US, Japan, South Korea, Taiwan	Lu et al. 2017.
	PCDDs and PCDFs	MSW	Europe	Dong et al. 2018
	Dioxins	MSW	Sri Lanka	Dilshani et al. 2019

Table B-5 *Specific impacts of incineration on human health (continued)*

Impact Category	Impact Description	Material	Location	Source
Climate Change	Carbon monoxide (CO), Nitrous oxides (NO_x)	MSW	Europe	Dong et al. 2018
	Carbon monoxide (CO), Carbon dioxide (CO_2), Ethane, Ethene, Methane (CH_4)	Cotton	Spain	Molto et al. 2005
Heavy Metals	Cadmium (Cd), Mercury (Hg)	MSW	Europe	Dong et al. 2018
	Heavy metals	MSW	Sri Lanka	Dilshani et al. 2019
Respiratory Illness	Hydrogen chloride (HCl)	MSW	China, EU, US, Japan, South Korea, Taiwan	Lu et al. 2017.
	Hydrogen chloride (HCl)	MSW	Europe	Dong et al. 2018

Table B-6 *Specific impacts of mechanical recycling on human health*

Impact Category	Impact Description	Material	Location	Source
Air Pollution	non-methane volatile organic compounds (NMVOC equivalent)	MSW	Germany	Harish et al. 2021
Climate Change	Carbon dioxide equivalent (CO_2e)	MSW	Germany	Harish et al. 2021
	Carbon dioxide equivalent (CO_2e)	Cotton	Spain	Esteve-Turrillas and de la Guardia 2017

Table B-7 *Specific impacts of chemical recycling*

Solvent	Process	Material Type(s)	Description of Impacts	Source
AMIMICl[1]	lyocell	cotton	Organ toxicity: respiratory system, Serious eye damage/eye irritation, Skin corrosion/irritation	ThermoFisher Scientific, 2021i
ammonia	ammonolysis	polyester, nylon	Serious eye damage/eye irritation, Skin corrosion/irritation, Specific target organ toxicity (single exposure), Very toxic to aquatic environment	ThermoFisher Scientific, 2023f
carbamic acid	ammonolysis	polyester, nylon	Carcinogenicity, Respiratory system toxicity (single exposure), Skin corrosion/irritation, Serious eye damage/eye irritation	ThermoFisher Scientific, 2021c
carbon disulfide	viscose	cotton	Acute inhalation toxicity - vapors, Organ toxicity: central nervous system, liver, kidney, Reproductive toxicity, Serious eye damage/eye irritation, Skin corrosion/irritation, Toxic to aquatic organisms	ThermoFisher Scientific, 2023a

[1] 1-Allyl-3-methylimidazolium chloride

Table B-7 *Specific impacts of chemical recycling (continued)*

Solvent	Process	Material Type(s)	Description of Impacts	Source
cobalt acetate	methanolysis	polyester, nylon	Acute oral toxicity, Carcinogenicity, Germ cell mutagenicity, May cause long-term adverse effects in the aquatic environment, May cause long-term adverse effects in the environment, Reproductive toxicity, Respiratory and skin sensitization, Respiratory system toxicity (single exposure), Skin sensitization, Toxic to aquatic organisms	ThermoFisher Scientific, 2021a
ethanolamine	ammonolysis	polyester, nylon	Acute toxicity: oral, dermal, inhalation (vapors), Harmful to aquatic organisms, Listed as carcinogenic, May cause long-term adverse effects in the aquatic environment, Respiratory system toxicity (single exposure), Serious eye damage/eye irritation, Skin corrosion/irritation	ThermoFisher Scientific, 2021b
ethylamine	aminolysis	polyester, nylon	Causes digestive and respiratory tract irritation with possible burns, Causes eye and skin irritation and possible burns, Harmful if swallowed or absorbed through the skin, Target organs: kidneys, heart, liver, lungs, eyes	ThermoFisher Scientific, 2008
ethylene glycol	glycolysis	polyester, nylon	Acute oral toxicity, Central nervous system toxicity (single exposure), Listed as carcinogenic, Liver and kidney toxicity (repeated exposure), Toxic to aquatic organisms	ThermoFisher Scientific, 2021d

Table B-7 *Specific impacts of chemical recycling (continued)*

Solvent	Process	Material Type(s)	Description of Impacts	Source
formic acid	acid hydrolysis	polyester, nylon	Acute oral toxicity, Acute inhalation toxicity - vapors, Harmful to aquatic organisms, Listed as carcinogenic, Skin corrosion/irritation, Serious eye damage/eye irritation	ThermoFisher Scientific, 2022
glacial acetic acid	aminolysis	polyester, nylon	Listed as carcinogenic, Serious eye damage/eye irritation, Skin corrosion/irritation, Toxic to aquatic organisms	ThermoFisher Scientific, 2021l
hydrochloric acid	acid hydrolysis, alkaline hydrolysis	polyester, nylon	Serious eye damage, Specific target organ toxicity (single exposure), Skin corrosion, Toxic to aquatic organisms	ThermoFisher Scientific, 2015a
lead oxide	methanolysis	polyester, nylon	Acute oral, dermal, and inhalation toxicity, Carcinogenicity, May cause long-term adverse effects in the aquatic environment, Reproductive toxicity, Specific target organ toxicity (repeated exposure), Very toxic to aquatic organisms	ThermoFisher Scientific, 2015c

Table B-7 *Specific impacts of chemical recycling (continued)*

Solvent	Process	MaterialType(s)	Description of Impacts	Source
magnesium acetate	methanolysis	polyester, nylon	Listed as carcinogenic	ThermoFisher Scientific, 2021e
methanol	methanolysis	polyester, nylon	Acute oral, dermal, and inhalation toxicity, Defects in fetus development in experimental animals, Immediate and delayed development defects in experimental animals, Specific target organ toxicity (single exposure), Toxic to aquatic organisms	ThermoFisher Scientific, 2015b
methylamine	aminolysis	polyester, nylon	Acute inhalation toxicity - vapors, Acute oral toxicity, Serious eye damage/eye irritation, Skin corrosion/irritation, Specific target organ toxicity (single exposure)	ThermoFisher Scientific, 2024
NMMO[2]	lyocell	cotton	Organ toxicity: respiratory system, Serious eye damage/eye irritation, Skin corrosion/irritation	ThermoFisher Scientific, 2020c
nitric acid	acid hydrolysis	polyester, nylon	Acute inhalation toxicity - vapors, Large amounts will affect pH and harm aquatic organisms, Listed as carcinogenic, Serious eye damage/eye irritation, Skin corrosion/irritation	ThermoFisher Scientific, 2021f

[2] n-methylmorpholine-N-oxide

Table B-7 *Specific impacts of chemical recycling (continued)*

Solvent	Process	Material Type(s)	Description of Impacts	Source
polyphosphoric acid	glycolysis	polyester, nylon	Listed as carcinogenic, May cause long-term adverse effects in the aquatic environment, Respiratory system toxicity (single exposure), Serious eye damage, Skin corrosion/irritation, Toxic to aquatic organisms	ThermoFisher Scientific, 2021g
potassium hydroxide	alkaline hydrolysis	polyester, nylon	Acute oral toxicity, Large amounts will affect pH and harm aquatic organisms, Listed as carcinogenic, Respiratory system toxicity (single exposure), Serious eye damage/eye irritation, Skin corrosion/irritation	ThermoFisher Scientific, 2023c
potassium sulfate	aminolysis	polyester, nylon	Listed as carcinogenic, Toxic to aquatic organisms	ThermoFisher Scientific, 2021m
sodium acetate	aminolysis	polyester, nylon	Listed as carcinogenic, Toxic to aquatic organisms	ThermoFisher Scientific, 2021h
sodium glycolate	glycolysis	polyester, nylon	Not considered hazardous chemical	ThermoFisher Scientific, 2021j
sodium hydroxide	alkaline hydrolysis	polyester, nylon	Large amounts will affect pH and harm aquatic organisms, Listed as carcinogenic, Respiratory system toxicity (single exposure), Serious eye damage/eye irritation, Skin corrosion/irritation	ThermoFisher Scientific, 2023b

Table B-7 *Specific impacts of chemical recycling (continued)*

Solvent	Process	Material Type(s)	Description of Impacts	Source
sulfuric acid	acid hydrolysis, alkaline hydrolysis	polyester, nylon	Listed as carcinogenic, Respiratory system toxicity (single exposure), Serious eye damage/eye irritation, Skin corrosion/irritation, Toxic to aquatic organisms	ThermoFisher Scientific, 2023d
terephthalic acid	neutral hydrolysis, aminolysis	polyester, nylon	Listed as carcinogenic, Respiratory system toxicity (single exposure), Serious eye damage/eye irritation, Skin corrosion/irritation, Toxic to aquatic organisms	ThermoFisher Scientific, 2020a
trifluoroacetic acid	acid hydrolysis	polyester, nylon	Acute inhalation toxicity - vapors, Harmful to aquatic organisms, Listed as carcinogenic, May cause long-term adverse effects in the aquatic environment, Serious eye damage/eye irritation, Skin corrosion/irritation	ThermoFisher Scientific, 2023e
zinc acetate	glycolysis, methanolysis	polyester, nylon	Acute oral toxicity, Listed as carcinogenic, May cause long-term adverse effects in the aquatic environment, May cause long-term adverse effects in the environment, Serious eye damage, Toxic to aquatic organisms	ThermoFisher Scientific, 2021k
zinc sulfate	viscose	cotton	Acute oral toxicity, Organ toxicity: heart, blood, Serious eye damage/eye irritation, Very toxic to aquatic organisms	ThermoFisher Scientific, 2020b

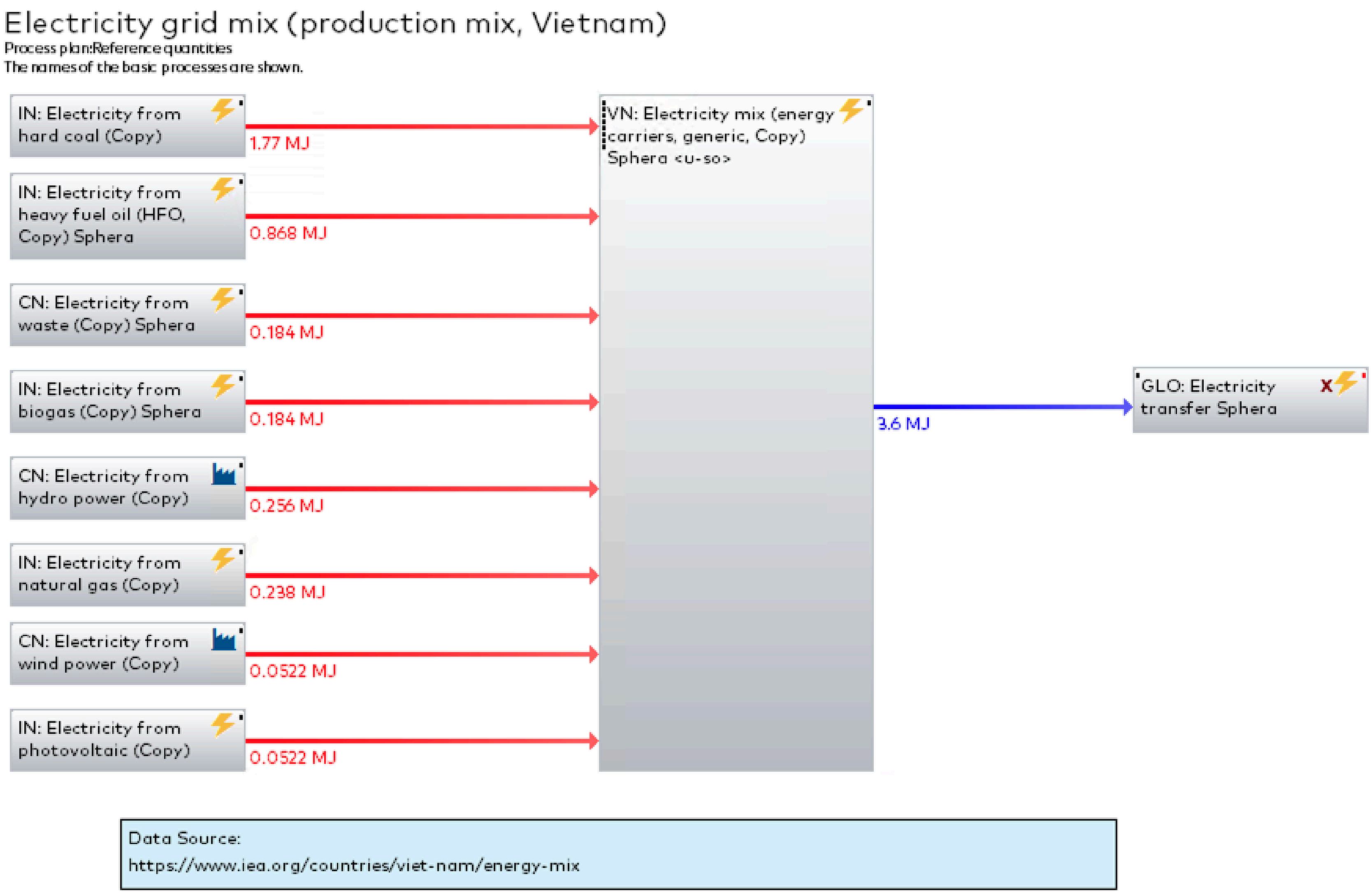

Figure B-1 *Vietnamese energy grid model built in LCA for Experts*

Appendix C - Supplier Survey Documentation

A survey for suppliers was designed with the intention of supplementing the information provided in the Higg FEM results and furthering our understanding of the current waste management practices in Vietnam. The survey was sent by Patagonia through their supply chain management and communication tool (CR360). An initial email was sent to suppliers providing context so they would be aware and more willing to participate. Patagonia received a 100% response rate.

Questions

1. Do you incinerate textile / fabric waste onsite?
   a. If yes, do you have filtration / scrubbing technology in place?
2. Do you landfill textile / fabric waste?
3. Do you have a contracted textile waste hauler/recycler?
   a. If yes, who is your textile waste recycler/hauler?
4. What's the largest influence over textile disposal methods?
   a. If other, please specify:

Results

Number	Question	Response
1	Do you incinerate textile / fabric waste onsite?	100% No
2	Do you landfill textile / fabric waste?	100% No
3	Do you have a contracted textile waste hauler/recycler?	94% Yes * 6% No
4	What's the largest influence over textile disposal methods?	69% 'Local Policies and Regulations' 31% 'Cost'

*Note: Waste hauler names have been omitted for confidentiality purposes.