Rakib Ahmed

Sustainable Clothing Systems: A Comparative Life Cycle Assessment of T-Shirts Made from Primary and Recycled Materials

Master's thesis in Industrial Ecology
Supervisor: Johan Berg Pettersen
Co-supervisor: Kim Rainer Mattson
June 2024

Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

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Acknowledgement

First of all, i would like to express my gratitude to God for giving me such a wonderful opportunity to receive a world-class education at NTNU and to experience the picture-perfect natural beauty of Norway and its wonderful people. Moving 9000 km away from home, friends, and family, and resuming academic life after a while, was challenging but immensely rewarding. I consider this transition one of the best decisions i have ever made.

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Abstract

The global clothing industry puts an enormous strain on the environment by consuming natural resources, causing 10% of global GHG emissions, and polluting air, soil, and water with various chemicals and fertilizers. Additionally, it generates a significant amount of waste every year. Currently the clothing industry is predominantly linear, with only 1% of material cycled back into new clothing, highlighting the potential of recycling as a promising circular economy strategy to reduce the demand for primary raw materials and decrease waste.

This study investigates the material flows of t-shirts imported into the Norwegian clothing system, from fibre production to end-of-life to estimate how much material can be recycled and reintroduced into the production of new t-shirts. Material flow analysis (MFA) was employed to systematically identify flows and processes across the system, providing insights into waste generation throughout the entire supply chain. The results of the MFA were then used as a base for performing a life cycle assessment (LCA). An extended lifecycle model was developed to encompass two lifecycles, capturing the benefits of reusing recycled materials in new t-shirts compared to a linear system where t-shirts are produced from primary materials and end up as residual waste.

Results from the MFA indicate that if a cotton t-shirt is separately collected in the Norwegian clothing system after the use phase, 27% of the initial fibre material required to produce a t-shirt can be recycled and repurposed in the production chain of the next t-shirt. This recycled fibre brings a 3-13% environmental benefit to the system across five impact categories: Climate change, ecotoxicity, land use, water use and energy use. For polyester t-shirts, this recovery percentage is 29%, but the achieved environmental benefit is minimal. Scenario analysis showed that the environmental performance of the recycling product system can be significantly improved to 4-29% across impact categories by increasing the rate of separate collection, optimizing processes to reduce waste at production stages, and recycling pre-consumer waste.

Through the integrated approach of using MFA and LCA, this thesis provides a comprehensive understanding of the clothing system, especially in terms of waste generation and opportunities for achieving the potential of a recycling system through material recovery and environmental benefits. These insights are highly relevant for transforming the predominantly linear system into a more circular one.

Sammendrag

Den globale klesindustrien legger en enorm belastning på miljøet ved å konsumere naturlige ressurser, forårsaker 10% av globale klimagassutslipp, og forurenser luft, jord og vann med ulike kjemikalier og gjødsel. I tillegg genererer den en betydelig mengde avfall hvert år. For tiden er klesindustrien overveiende lineær, med bare 1% av materialet syklet tilbake inn i nye klær, som fremhever potensialet ved resirkulering som en lovende strategi for sirkulær økonomi å redusere etterspørselen etter primære råvarer og redusere avfall.

Denne studien undersøker materialstrømmene til t-skjorter importert til det norske klessystemet, fra fiberproduksjon til endt levetid for å estimere hvor mye materiale som kan resirkuleres og gjeninnført i produksjonen av nye t-skjorter. Materialstrømanalyse (MFA) ble brukt for å systematisk identifisere strømmer og prosesser på tvers av systemet, og gi innsikt i avfallsgenerering gjennom hele forsyningskjeden. Resultatene fra MFA ble deretter brukt som en grunnlag for å utføre en livssyklusvurdering (LCA). En utvidet livssyklusmodell ble utviklet for å omfatte to livssykluser, for å fange opp fordelene ved å gjenbruke resirkulerte materialer i nye t-skjorter sammenlignet med et lineært system hvor t-skjorter er produsert av primærmaterialer og ender opp som restavfall.

Resultater fra MFA indikerer at dersom en bomulls t-skjorte samles separat i det norske klessystemet etter bruksfasen, kan 27% av det opprinnelige fibermaterialet som kreves for å produsere en t-skjorte resirkuleres og gjenbrukes i produksjonskjeden til neste t-skjorte. Denne resirkulerte fiberen gir en miljøgevinst på 3-13% til systemet på tvers av fem påvirkningskategorier: klimaendringer, økotoksisitet, arealbruk, vannbruk og energibruk. For polyester t-skjorter, er denne gjenvinningsprosenten 29%, men den oppnådde miljøgevinsten er minimal. Scenarioanalyse viste at miljøytelsen til resirkuleringsproduktsystemet kan forbedres betydelig til 4-29% på tvers av påvirkningskategorier ved å øke frekvensen av separat innsamling, optimalisere prosesser for å redusere avfall i produksjonsstadiene, og resirkulering av pre-consumer avfall.

Gjennom den integrerte tilnærmingen med å bruke MFA og LCA, gir denne oppgaven en omfattende forståelse av klessystemet, spesielt når det gjelder avfallsgenerering og muligheter for å oppnå potensialet til et resirkuleringssystem gjennom materialgjenvinning og miljøfordeler. Denne innsikten er svært relevant for å transformere det overveiende lineære systemet til en mer sirkulær.

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1 Introduction

Apparel, crafted from various natural and synthetic fibres, comes in various shapes, colors, and qualities to satisfy specific needs such as comfort, safety, cultural identity, social status, or to offer protection against extreme weather. This apparel industry operates within a complex global value chain. About 60% of total textiles including apparel and home textiles are produced in South and East Asian countries, and approximately 64% of total produced textiles are exported to regions like the EU, North America and South America for the final consumption (World Bank, 2021). Also the components including fibres, yarns, fabrics, trims and accessories often originate from different parts of the world and assembled into finished garments in production units far from where the components were made. Influenced by high population growth, higher income per capita, improved living standards, the fast fashion trend attributed to cheap production cost and less durable products, global textile production and consumption have doubled over the last two decades and reached to 114 million tonnes in 2021 (Shirvanimoghaddam et al., 2020, Statista, 2023). Under business-as-usual scenario, the global textile industry is expected to continue growing, particularly in developing countries, leading to an increase in non-renewable resource inputs to 300 million tonnes per year by 2050 from 98 million tonnes in 2015. This consumption of non-renewable resources includes oil to produce synthetic fibres, fertilizers for cotton cultivation, and chemicals for different manufacturing processes (Ellen MacArthur Foundation, 2017, Terinte et al., 2014). This surge in production and consumption imposes significant environmental burdens. For instance, the textile industry's global supply chain is now the fourth highest consumer of primary raw material and water in the EU, after food, housing and transport industry (European Environment Agency, 2019). Globally, textile production is responsible for about 20% of freshwater pollution and emits 1.7 billion tonnes of greenhouse gases every year representing 10% of the global total (Niinimäki et al., 2020). On a product level, producing a single t-shirt requires 2,700 litres of fresh water which is equivalent to one person's drinking need for 2.5 years (European Parliament, 2020).

Like most other industries, the textile industry also represents a linear economic model- take, make, waste- resulting in about 92 million tonnes of waste annually (Niinimäki et al., 2020). Of this 73% end up in landfill or incinerated while only 25% discarded garments are collected separately for recycling and reuse (Ellen MacArthur Foundation, 2017). Only 1% of total waste is recycled into new garments (Textile Exchange, 2020). Textile reuse and recycling not only to increase the lifetime of the product but also reduce the production of virgin raw materials. A variety of technologies for textile recycling have been developed and are well practiced, and some are under development for the valorization of textile products (Hammar et al., 2023, Juanga-Labayen et al., 2022, Schmidt et al., 2016). In addition to bringing energy and resource-efficient, economically profitable recycling technologies and prolonging a product's lifetime through reuse, resale and renting, it is also important to evaluate the environmental performance of a product system based on different end-of-life pathways.

Life cycle assessment (LCA) is a useful tool to quantify potential environmental impact of a product throughout its entire life cycle, considering material and energy flows, waste generation, and emissions from resource extraction to end-of-life disposal (Hellweg and Milà i Canals, 2014). Applying this method to the Swedish clothing system, researchers have revealed significant variation in the climate change impact associated with different garments ranging from 1 kg CO_2-eq for socks to about 20 kg CO_2-eq per jacket. It was determined that certain production stages, such as wet processing and fibre production are substantial contributors to a product's carbon footprint (Sandin, Roos, et al., 2019). However, this particular study did not explore different end-of-life scenarios such as reuse and recycling, which are essential in understanding the potential for sustainability within the apparel industry.

A study investigating the treatment of discarded textiles through three end of life scenarios including reuse, recycling and incineration across different fibre types established that reuse offers the most environmental benefits, followed by recycling, with incineration as the least favorable option (Schmidt et al., 2016). The recycling process has developed with advancements in mechanical, chemical, and thermochemical techniques over the years to transform textile waste into various products. These products including recycled polymers, fibres, yarn, and biofuels are not only suitable for the textile industry but also beneficial for other sectors. The environmental footprints of these innovative recycled methods have been analyzed through LCA studies (Schmidt et al., 2016; Hammar et al., 2023, Spathas, 2017, Lee et al., 2023). Additionally, LCAs have been applied to novel practices such as making textile fibres from non-textile products, exemplified by converting PET bottles into usable fibres (Sun et al., 2024). Despite extensive comparative LCAs across different products and end-of-life treatments, as well as individual LCAs on various technologies, a comparison of the environmental impacts of garments made from virgin versus recycled materials remains unexplored.

The current methodological framework of LCA studies on textile waste treatments considers discarded textile waste as the starting point and recycled content as the end point inside the system boundary. This approach raises two key concerns. The first is the allocation of environmental burdens to waste materials, where the most common cut-off allocation method considers waste feedstock as having no environmental burden. This practice fails to reflect the true environmental cost carried by these materials. This is visually shown in Figure 1.1, which presents two distinct life cycles from two LCA studies: the first captures the journey from virgin material production to waste generation, while the second begins with waste as a 'burden-free'

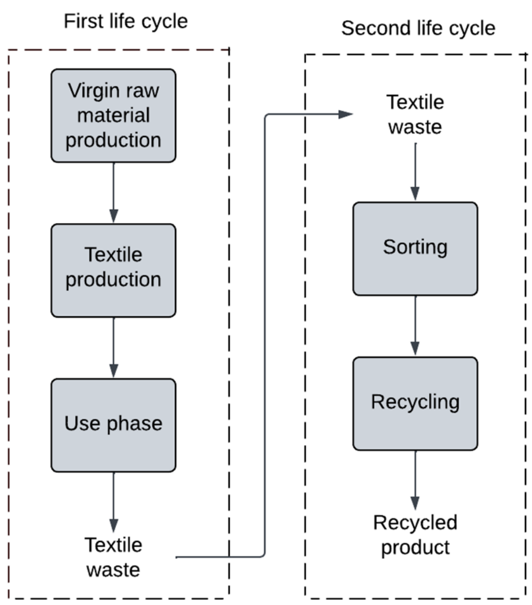


Figure 1.1: System boundary and allocation of environmental burden in two life cycles.
(Source: Adapted from Sun et al. (2024))

material, neglecting its actual contribution to the recycling process. Additionally, since these two studies address separate life cycles, the extent to which waste collected from the first life cycle is actually recycled in the second life cycle remains outside the scope of both studies.

Research on the material flows of textile goods at a national scale is limited. However, the study by Mora-Sojo et al. (2023) stood out by analyzing the material flows of the household clothing system within Norway for 2018 and proposed a circular model through the concept of renting out second-hand clothes. Despite its contribution, the study did not investigate the recycling potential across different fiber types within the Norwegian context.

To address the identified research gaps - the challenge of burden allocation on waste materials, the need for a comprehensive view of material flows across the supply chain and the environmental impact analysis of recycled products related to their virgin variants- this thesis employs a model with expanded system boundary. This approach treats the treatment of waste materials and their subsequent utilization in a new life cycle as an integral part of the initial life cycle. This expanded LCA framework encompasses all processes across two life cycles, capturing mass flows, process losses, and the potential volume of discarded textile waste from Norwegian households that can be recycled, following the share of materials into different waste streams as estimated by Mora-Sojo et al. (2023). This thesis conducts LCAs on t-shirts made of cotton and polyester. These fibres are chosen due to their prevalence in the industry, with polyester (54%) and cotton (22%) holding the largest market share globally (Textile Exchange, 2020).

Additionally, t-shirts are one of the most common garments found in wardrobes worldwide (Barnard, 2020). The life cycle inventory of t-shirt production is also well-documented in several existing studies, providing a solid foundation for analysis in this thesis. Selecting a relatively simpler and common product type allows this study to focus more effectively on system modelling, including the analysis of recycled products across various scenarios. Given these considerations, this study is driven by the following research questions:

Research question 1: To what extent can the fibres in a t-shirt be recycled under the existing system, and how does this affect the demand for primary fibres in the recycled product compared to a t-shirt made entirely of virgin fibres?

Research question 2: What environmental benefits can be achieved if a t-shirt is recycled into a new one, rather than incinerated, considering two different product systems?

Research question 3: How might the environmental performance of these product systems be improved?

Research question 4: What is the environmental benefit if the Norwegian clothing system can adopt a recycling product system?

In this study, Research question 1 will be addressed by material flow analysis (MFA) across the entire supply chain. To explore Research Question 2 and 4, a comparative LCA will be conducted on two product systems for t-shirts- linear and recycling- for both cotton and polyester compositions. Scenario analysis adjusting key parameters within the studied systems will be employed to answer Research question 3.

Disclaimer

This thesis builds upon the author's previous specialization project conducted in Autumn 2023, titled 'Advancing circular economy strategy in textile waste management system'. That project work analyzed the material flows within the Norwegian clothing system and developed two circular scenarios, including recycling to promote greater circularity. Although this thesis is an independent work, some of the content in the introduction and background sections is inspired by the previous project report.

2 Background

This section provides background information on the various types of textile waste, waste management practices, different sorting and recycling methods, and relevant EU regulations.

2.1 Textile waste management

As the textile industry continues to expand, the generation of waste at various stages is also increasing rapidly. In the EU alone, 5.2 million tonnes of clothing and footwear waste were generated in 2019, which equates to 12 kg per capita. Research has revealed that about 70% of these disposed items remain usable when they end up in landfills (Moazzem, Wang, et al., 2021).

An effective waste management strategy begins with identifying waste and its characteristics at different stages. Textile waste can be classified into three types: pre-consumer waste, post-consumer waste, and industrial waste (Cuc and Vidovic, 2014, Juanga-Labayen et al., 2022). Pre-consumer waste, often referred to as 'clean waste', generally originates from manufacturing stages such as spinning, knitting, weaving, dyeing and garment production. In contrast, post-consumer waste consists of items discarded by consumers because they are no longer wanted, either due to a lack of functionality or because they are out of trend. Some good-quality garments or fabrics can be recovered from this category and are suitable for reuse and recycling. Industrial waste on the other side, is often considered 'dirty waste' and is generated from commercial and industrial applications (Juanga-Labayen et al., 2022; RB, 2014). Since this thesis focuses on t-shirts, pre- and post-consumer waste will be the primary focus, while industrial waste will be excluded from the scope.

2.1.1 Handling of post-consumer waste

Collection of textile waste

After the use phase, consumers discard their garments as residual waste or into separate collection containers. In the EU, most separate collection is managed by charitable organizations and private collectors. The primary method of collecting textile waste is through bring banks located at various collection points. Additionally, kerbside collection, as well as collection at sorting and recycling centers, are also implemented (Miljøstyrelsen, 2020).

Sorting of textile waste

After separate collection, textiles need to be categorized based on their usability, color, composition, and other factors. The efficiency of this sorting process directly affects the quality and quantity of garments segregated for reuse and recycling. Currently, sorting is predominantly a manual process that is both time-consuming and labor intensive, making it a costly operation (Riba et al., 2020). Additionally, the sorting process often faces other challenges. For example, fabric composition mentioned on garments' labels are frequently destroyed, faded, or missing, making it difficult for sorters to identify the correct fiber composition. Identifying the true composition of garments is crucial for recycling, as the entire process is highly sensitive to the fiber composition. To increase the efficiency of this sorting process, most textile sorters only accept clean textiles, ensuring they are free of additional accessories such as zippers, buttons, or any motifs (Dukovska-Popovska et al., 2023). With an increased emphasis on circularity and mandatory separate collection by 2025 onward, a significant shift from manual to automatic sorting system is predicted. Innovative projects are now exploring the application of near-infrared (NIR) technology, robotics, and artificial intelligence (AI) to boost automation in textile sorting (Louise et al., 2023).

Recycling of textile waste

After detailed sorting, garments are segregated for reuse or recycling. Textile reuse and recycling can avoid the production of virgin materials and reduce the amount of waste. Figure 2.1 summarizes different types of reuse and recycling routes that have the potential to slow and close the loop in the textile industry. It illustrates the journey of garments from raw material production to possible end-of-life treatments. Green and red flows indicate pre-consumer and post-consumer waste, respectively. Reuse of used garments can be done in many ways, including consumer-to-consumer transfer through borrowing, inheriting, exchanging, and trading using channels like social media or e-commerce websites (Sandin and Peters, 2018, Mora-Sojo et al., 2023). Some portion of separately collected garments is also sent to second-hand retail shops for reuse. On the other hand, recycling can be categorised by different means, typically based on type of treatments: mechanical and chemical recycling. Mechanical treatment involves cutting, shredding, and making new fibres, whereas chemical treatment involves depolymerization through chemical reactions.

Recycling can also be classified based on the quality and economic value of the recycled product such as upcycling, downcycling, closed-loop, and open-loop recycling. Upcycling generates products of higher value or quality than the original product. For example, fibre and fabric recycling that produces material of lower quality is terms of fibre length is considered downcycling until it is mixed with virgin materials to improve quality (Sandin and Peters, 2018). In practice, to be reutilized in clothing, mechanically recycled fiber

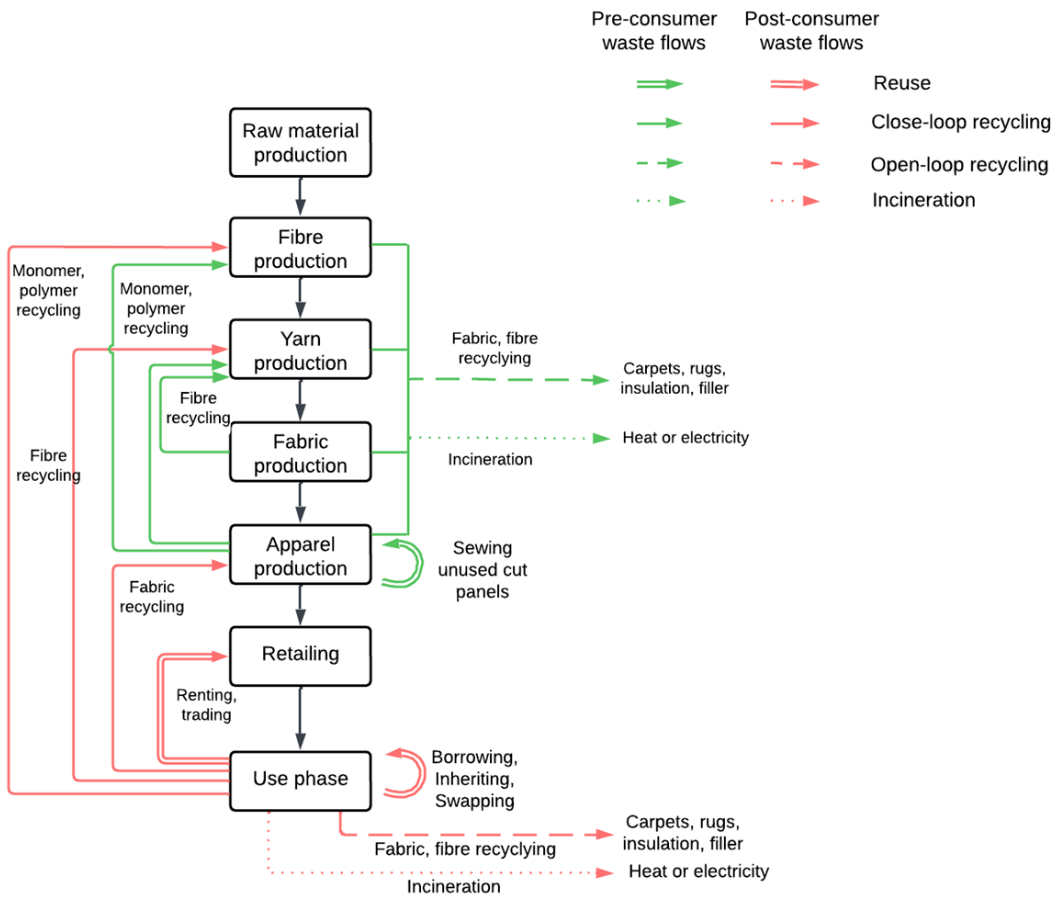


Figure 2.1: Simplified classification of different types of textile reuse and recycling routes.
(Source: Adapted from Sandin and Peters (2018))

needs to be mixed with primary fibers to achieve the required yarn strength. Conversely, monomer, oligomer and polymer recycling that produce materials of similar quality to primary material can be considered upcycling (Sandin and Peters, 2018). Closed-loop recycling involves using recycled materials in the production of similar materials, whereas open-loop or cascading recycling generates products for different applications, such as carpets, rugs, and insulation materials (Schmidt et al., 2016, Sandin and Peters, 2018) as illustrated in figure 2.1. Incineration for energy recovery is considered the last option for waste treatment.

2.1.2 Handling of pre-consumer waste

A substantial amount of pre-consumer waste is generated in the production of textile goods in manufacturing countries (Li et al., 2021, Khairul Akter et al., 2022). Similar to post-consumer waste, pre-consumer waste management also faces numerous challenges.

According to Khairul Akter et al. (2022), Bangladesh, the second highest garment manufacturing country for the international market, struggles with traceability of waste generated along the production stages. Their study highlighted a significant underground market activities where dealers illegally acquire waste materials referred to as 'stock lot', which includes excess fabrics, unused garments, and cutting waste. These transactions often bypass official channels due to regulations against these type of dealings to protect domestic production targeted for local consumers. This informal market thrives due to a lack of effective policy and the absence of technologies equipped to deal with the complex mix of fibres, dyes and chemicals present in textile waste. A small portion of these pre-consumer waste is turned into filling materials for cushion, mattresses, and carpets or made into smaller garments by rectifying defects in cut panels, while the majority of it ends up in landfills (Textile Today, 2022).

In China, textile waste management is similarly challenging. According to Li et al. (2021), approximately 50% of waste generated by Chinese textile manufactures is sold to informal individual recycling enterprises. These enterprises often operate within a grey market, further distributing the waste to second-hand textiles processing companies. This practice is driven by several factors: textile factories are not equipped with the necessary arrangements to handle such waste properly, and their dependency on manual labor makes the processing of low-valued waste economically unsustainable. There are some practices of high-quality textile recycling, which involves reusing the fabric or mechanically breaking it down into small pieces to make few fibre. However, chemical recycling requires significant technological investment and infrastructure, making this practice seldom implemented (Li et al., 2021).

2.2 EU regulations and Waste hierarchy

Waste Framework Directive (2008/98/EC) was a pioneering steps by the EU to tackle the large amount of waste generated across all the industries including textiles. This directive focused on establishing a legislative framework for handing waste and encourages member countries to follow the waste hierarchy, which prioritizes actions based on their environmental performance. The waste hierarchy sets waste prevention as the best option, followed by reuse, recycling, incineration and disposal as a least preferred option (European council, 2008).

Recognizing the significant waste problem generated by the global textile industry and the potential for circularity, the textile sector was included in the EU's new circular economy action plan in march 2020 (European Commission, 2020). This action plan includes goals

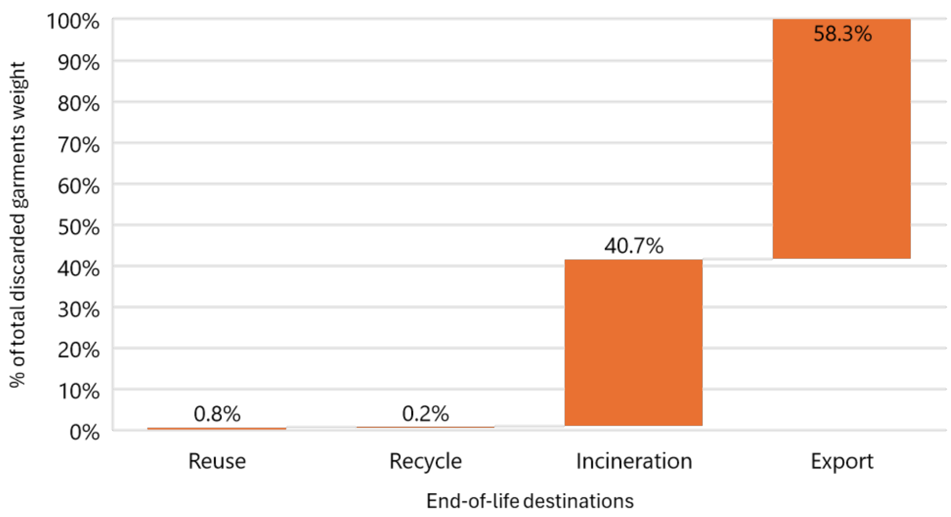


Figure 2.2: Waste management of Norwegian clothing system for 2018.
(Source: Based on the values from Mora-Sojo et al. (2023))

such as incentivizing circular business models, promoting reuse and repair, setting eco-design requirements, establishing harmonized Extended Producer Responsibility (EPR), and enhancing information transparency (European Commission, 2022).

2.3 Norwegian textile consumption and waste management

Consumable products used in Norway, including clothing, home appliances, personal care products, and cleaning agents, account for utilizing approximately 26.6 million tonnes of resources, encompassing fossils, ores, minerals, and biomass (Circular Norway, 2020). Studies by Mora-Sojo et al. (2023) and Watson et al. (2020) estimated the consumption of clothing to be around 61,000 tonnes in 2018, with 88% being used for household purposes. 79% of separate collections are managed by charitable organizations, while the remaining 21% are handled by private collectors and municipal waste companies. Approximately 22,200 tonnes of discarded clothes end up in residual waste, destined for incineration. As shown in figure 2.2, around 32,400 tonnes of clothing are exported to other countries for further sorting, while only 1% of separately collected clothing remains in Norway for reuse and recycling (Mora-Sojo et al., 2023, Watson et al., 2020). Regarding product categories, t-shirts and underwear are the most consumed items by quantity, accounting for 44% of total consumption(Mora-Sojo et al., 2023).

3 Methodology

This section outlines the methodology utilized to answer the research questions for this study. Subsection 3.1 defines the scope of the research, including product systems, case studies and system boundaries. Subsection 3.2 explains the methodology of material flow analysis (MFA), conducted to answer research question 1 by determining the material flows of t-shirts across the entire supply chain. These flows were then utilized in the inventory development of the life cycle assessment (LCA), which addresses research question 2. Subsection 3.3 covers the LCA methodology, followed by the development of complementary scenarios in subsection 3.4, aiming to address research question 3. Combined MFA and LCA were employed to address research question 4 by determining Norwegian consumption of t-shirt goods and the impact related to it.

3.1 Scope of the research

The objective of the MFA and LCA is to quantify the material flows associated with the production, use, disposal, and end-of-life treatment of two t-shirts (T-shirt 1 and T-shirt 2) and compare the environmental impacts between two product systems. Based on the purpose of the study, the temporal boundary was set to encompass two consecutive lifecycles of two t-shirts. This means after the end-of-life treatment of T-shirt 1, the lifecycle of T-shirt 2 will begin, and both MFA and LCA will be conducted over these two lifecycles. Considering two lifecycles provides a clear understanding of how much material from t-shirt 1 can be recycled and used in t-shirt 2. This analysis is essential for understanding the potential reduction in resource use and emissions in the recycling product system compared to the linear system.

Figure 3.1 illustrates the system boundaries for the baseline and recycling product systems for both cotton and polyester cases. Both product systems include the production, use and disposal phases for each t-shirt. In the baseline system, both t-shirts end up in residual waste and are then incinerated. In the recycling product system, after the use phase, t-shirt 1 is separately collected for sorting and recycling. The recycled material is then utilized in the production of a new t-shirt (T-shirt 2). Therefore, this study examines two product systems for the following cases, as summarized in table 3.1.

A. **Cotton Case:**

- **Linear Product System:** Both t-shirts (T-shirt 1 and T-shirt 2) are made entirely of primary cotton fibers.
- **Recycling Product System:** T-shirt 1 is made of primary cotton, while T-shirt 2 is made of a mixture of primary and recycled cotton fibers recovered from t-shirt 1.

B. **Polyester Case:**

- **Linear Product System:** Both t-shirts (T-shirt 1 and T-shirt 2) are made entirely of primary polyester fibers.

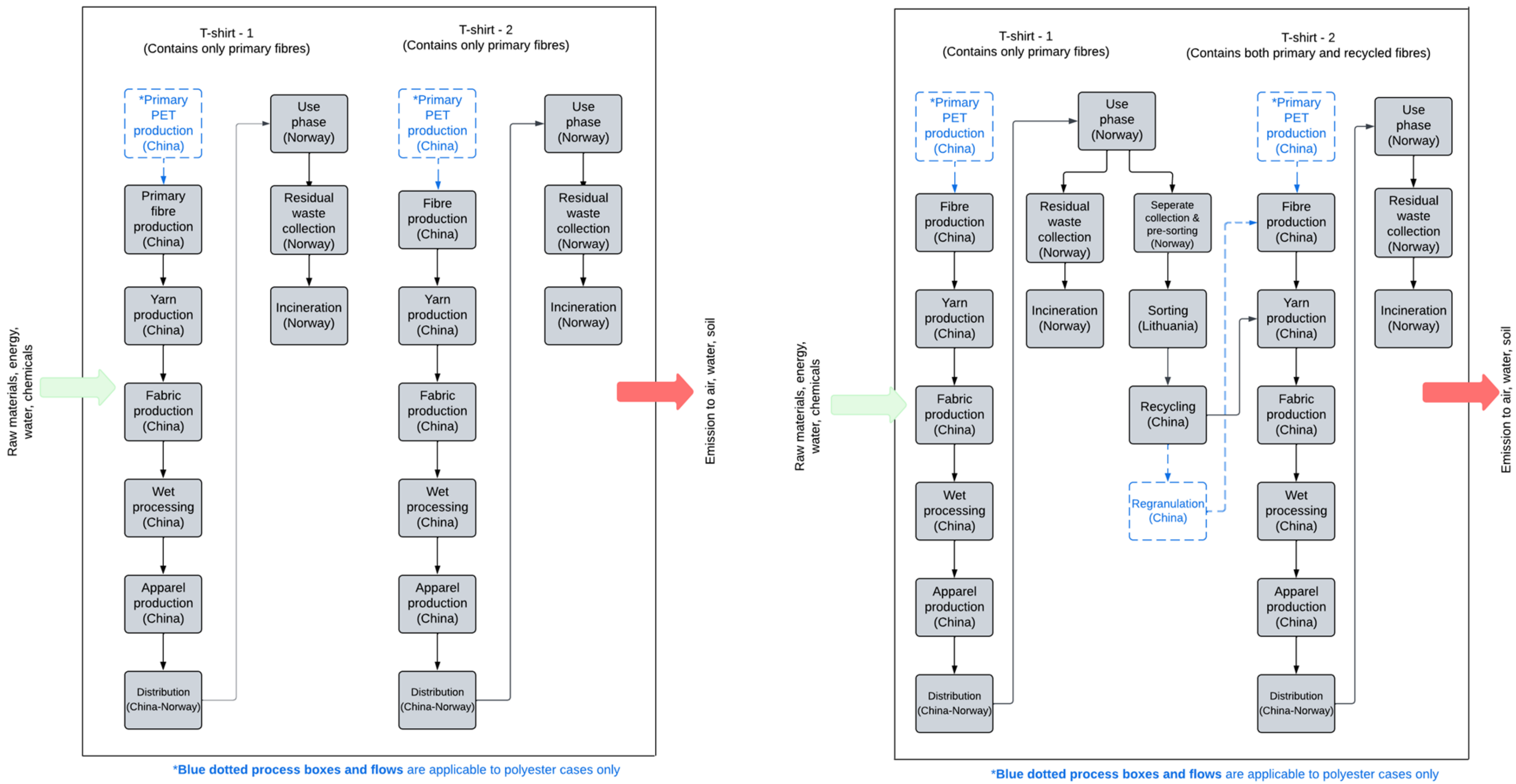
- **Recycling Product System:** T-shirt 1 is made of primary polyester, while t-shirt 2 is made of a mixture of primary and recycled polyester fibers recovered from t-shirt 1.

Table 3.1: Overview of product cases and product systems.

Cases	**Linear Product System (Primary 2x)**	**Recycling Product System (Primary + Recycled)**
A. Cotton Case	Primary cotton t-shirt + Primary cotton t-shirt	Primary cotton t-shirt + Recycled cotton t-shirt
B. Polyester Case	Primary polyester t-shirt + Primary polyester t-shirt	Primary polyester t-shirt + Recycled polyester t-shirt

The spatial boundary of this study encompasses the global supply chain through which t-shirts are produced, consumed and treated at the end-of-life. All production stages of the t-shirts, from raw material production to distribution, are assumed to occur in China. This assumption is based on China's status as the highest exporter of knit t-shirts for several decades (OEC, 2023). Given the aim of conducting a comparative LCA in the Norwegian context, the use phase, discard, residual waste collection, and incineration are assumed to take place in Norway. Similarly, additional processes in the recycling product system such as separate collection, and pre-sorting are assumed to be performed in Norway. Moreover, after pre-sorting at separate collector's facilities, sorting is presumed to take place in Lithuania, reflecting the fact that the majority of the collected textiles in Norway are sent to Eastern European countries such as Poland, Lithuania, Estonia, and Bulgaria for detailed sorting (Watson et al., 2020). Lithuania is particularly chosen because this study utilizes material flows and life cycle inventory data from a textile sorting center located in Vilnius, Lithuania, as described by Nørup et al. (2019).

Both mechanical and chemical recycling processes are assumed to be carried out in China. This assumption is supported by several factors: China is the world's largest producer of textile products (OEC, 2022) and has significant infrastructure for recycling textile waste. In 2020, China recycled one-fifth of its 22 million tonnes of textile waste and aims to increase this rate to 30% to produce 3 million tonnes of recycled fibre by 2030 (The State Council, China, 2022). The Chinese government has made substantial investments to develop best recycling practices for the entire textile industry and has issued numerous regulations and standards for textile waste management to optimize the environmental performance (Li et al., 2021).



(a) Linear product system (Primary 2x)

(b) Recycling product system (Primary + Recycled)

Figure 3.1: System boundaries of (a) linear and (b) recycling product system for cotton and polyester cases.

Although these case studies and their respective product systems represent hypothetical scenarios that do not mirror any specific existing supply chain, the reasoning behind the geographical selection of supply chain operations is based on realistic global trade patterns in the textile industry to meet the purpose of this study. Additionally, the reuse of discarded clothing is intentionally excluded from the scope of this study. Numerous studies have already established that reuse offers the most significant environmental benefits compared to other end-of-life treatments (Koligkioni et al., 2018, Schmidt et al., 2016, Dahlbo et al., 2017). Therefore, this study focuses on evaluating the potential benefits that recycling can bring to the system.

3.2 Material flow analysis (MFA)

This subsection details the application of material flow analysis (MFA) to answer research question 1. The goals of these MFAs have been previously discussed in section 3.1. MFA systematically assesses the flows and stocks of materials within a specific system over time and space (Brunner and Rechberger, 2004). This section is divided into two subsections: subsection 3.2.1 presents the system definitions, while subsection 3.2.2 explains the methodology used to determine the flows.

3.2.1 System definition

In both the cotton and polyester cases, a white t-shirt weighing 110 grams, as shown in Figure 3.2, is considered as the final product consumed by the user. The weight and color of the t-shirt are based on the study by Sandin, Roos, et al. (2019), which provide comprehensive life cycle inventory data, detailed insights into the processing steps, and the material and energy flows involved in t-shirt production. Utilizing this data ensures consistency and reliability in the MFA for this thesis.

Figure 3.2: Reference T-shirt used for MFA and LCA modeling.
(Source : Sandin, Roos, et al., 2019)

Aligned with the system boundaries described in section 3.1, two system definitions were created as shown in figure 3.3 and 3.4 : one for the cotton case and another for the polyester case. The system definition for the cotton case involves 11 processes and 21 flows, while the polyester case involves 13 processes and 24 flows. Flows highlighted in green represent the material of t-shirt 1, while those in red represent t-shirt 2. These flows trace the journey of fibrous materials from production to disposal, and ultimately leading to either incineration or recycling at the end-of-life. In both cases, only one flow (A11-1b and A12-1a) contains both green and red colors, signifying that recycled material from t-shirt 1 is incorporated into the production chain of t-shirt 2. Both system definitions are almost identical except for two additional processes in polyester case: fibre production and regranulation of PET. In cotton case, the primary cotton fibres are sourced from outside the MFA system boundary, whereas in the polyester case, primary PET granulates come from outside the boundary. This setup enables a comparison of the demand for primary raw materials between the linear and recycled product systems.

Detailed description of each process along with their generated waste types, will be included in section 3.3.2, where the unit processes of the LCA study are discussed. The assumptions regarding the location of each operation are already explained in section 3.1. One important aspect to consider is the location of incineration operation. Although the system definition shows incineration as a single process for better visualization with fewer flows and processes, the actual locations for incineration will differ based on where the waste is generated. For instance, pre-consumer wastes from yarn, fabric, and apparel production are assumed to be incinerated in China, where production occurs. Similarly, discarded used t-shirts are projected to be incinerated in Norway, while waste from sorting processes is assumed to be incinerated in Lithuania. Different incineration locations will be taken into account when performing the LCA, but have no effect for the MFA.

As mentioned in section 3.1, these system definitions have been developed to capture material flows of two t-shirts across two lifecycles sequentially. The duration of one lifecycle is uncertain and not critical for this study. This uncertainty arises because lifespan of a t-shirt can vary significantly based on many factors such as wearing frequency, maintenance, and consumer behavior, which are difficult to standardize (Laitala and Klepp, 2020). The focus of this analysis is on the material flows and environmental impacts associated with the production, use and recycling of t-shirts, rather than the exact timeframe over which these processes occur. Therefore, the specific duration does not influence the overall conclusion about material recovery and environmental benefits. However, it is assumed that each t-shirt is used 30 times during its lifetime based on the study by Sandin, Roos, et al. (2019).

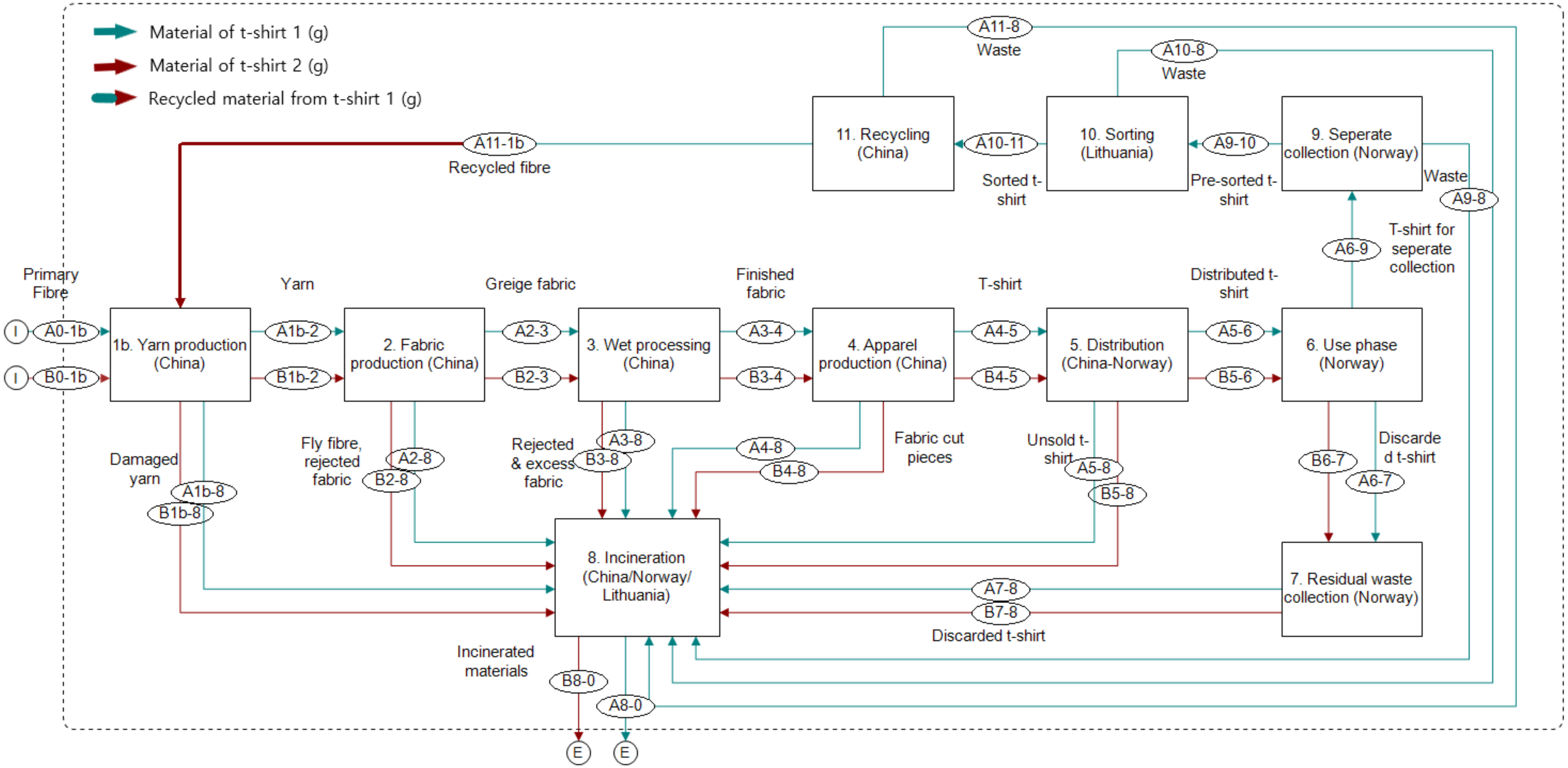


Figure 3.3: System definition for cotton case.

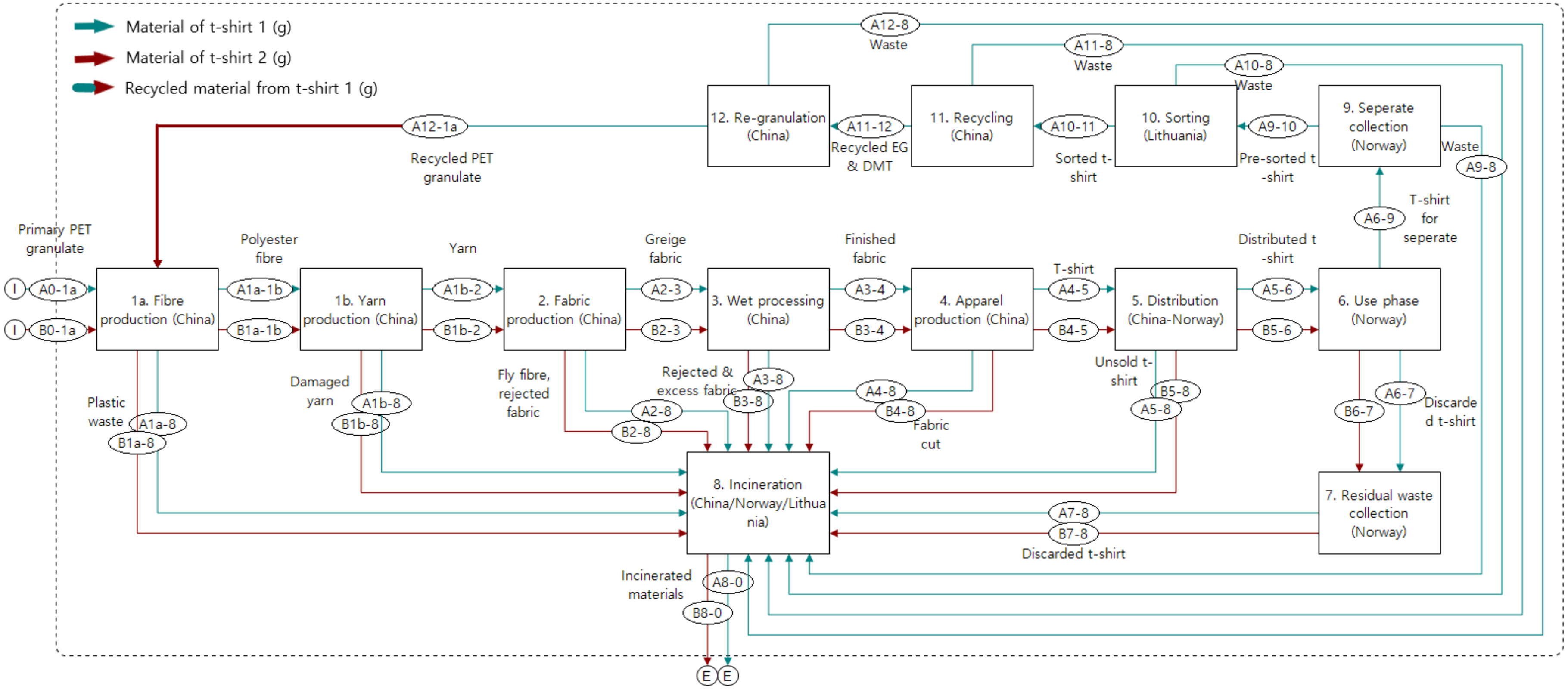


Figure 3.4: System definition for polyester case.

3.2.2 Determination of flows

This section provides a brief description of the mass balance principle for MFA and explains the approach followed to quantify the system. According to the law of conservation of matter, the total mass of inflows into any process equals the total mass of outflows plus the stock changes within the process (Brunner and Rechberger, 2004). Mathematically, the mass balance equation for any process k can be represented as follows:

$$\sum \text{inflow}_k = \sum \text{outflow}_k + \Delta S_k$$

where ΔS_k is the stock change. In this study, the stock change is assumed to be zero ($\Delta S_k = 0$) in all processes due to the uncertainty and lack of data related to the accumulation or depletion of materials. For instance, there is no quantitative studies in Norway or other Nordic countries regarding the increase or decrease of clothes in wardrobes (stock change, ΔS_k).

Material waste generated at different upstream and downstream processes is a key parameter for quantifying flows in the MFA models. This study conducts a product-level MFA, where the mass of two t-shirts is traced across the supply chain. Table 3.2 summarizes the parameters and main data sources used for quantifying these flows. The starting point for quantification is the weight of a t-shirt, which is 110 grams (indicated as a separate row in the table). Subsequent quantification proceeds through the upstream processes (rows above the use phase) and downstream processes (rows below the use phase), considering the waste percentages involved in each process.

Another important parameter in this study is the separate collection percentage, which determines the portion of a t-shirt that is separately collected for further processing. For instance, in the study by Mora-Sojo et al. (2023), it was estimated that around 60% of total discarded garments by Norwegian households are separately collected. This thesis utilizes this 60% separate collection rate in product-level material flows. Additionally, the determination of flows considers the percentage of clothing deemed unsuitable for further processing after pre-sorting and sorting processes as waste. The rest of the flows were estimated using the mass balance principle.

Table 3.2: Summary of parameters and their values used in system quantification.

Process	Parameter considered	Parameter value	Source	Corresponding case studies
1a. Fibre production	Process loss%	1.4%	Ecoinvent v3.8	Polyester
1b. Yarn production	Process loss%	16%	Moazzem, Crossin, et al. (2021)	Cotton
1b. Yarn production	Process loss%	4%	Moazzem, Crossin, et al. (2021)	Polyester
2. Fabric production	Process loss%	2%	Alam et al. (2023)	Both
3. Wet processing	Process loss%	11%	Alam et al. (2023)	Both
4. Apparel production	Process loss%	15%	Alam et al. (2023)	Both
5. Distribution	Process loss%	1%	Sandin, Roos, et al. (2019)	Both
6. Use phase	**Weight of the t-shirt**	**110 gram**	**Sandin, Roos, et al. (2019)**	**Both**
9. Separate collection	Collection rate% and process loss% for seperate collection & pre-sorting	60% & 1.2%	Mora-Sojo et al. (2023)	Both
10. Sorting	Process loss%	6.1%	Nørup et al. (2019)	Both
11. Recycling (Mechanical)	Process loss%	20%	Schmidt et al. (2016)	Cotton
11. Recycling (Chemical)	Process loss%	10%	Schmidt et al. (2016)	Polyester
12. Re-granulation	Process loss%	17.3%	Ecoinvent v3.8	Polyester

3.3 Life cycle assessment (LCA)

To evaluate the environmental impact of the clothing product systems, a life cycle assessment (LCA) was conducted in accordance with ISO 14040 and ISO 14044 (ISO, 2006). It helps identify opportunities to improve environmental performance by pinpointing hotspots within the product life cycle and supports product or process development, decision making, strategic planning and policymaking (Hellweg and Milà i Canals, 2014, ISO, 2006). LCA consists of four main stages: goal and scope definition, inventory analysis, impact assessment and interpretation. Figure 3.5 summarizes all these stages. The goal and scope of this study will be presented in section 3.3.1, the inventory of the studied system, allocation and chosen impact categories will be presented in sections 3.3.2, 3.3.3, and 3.3.4. Interpretation is integrated throughout the methodology, results and discussion to ensure a comprehensive understanding of the data.

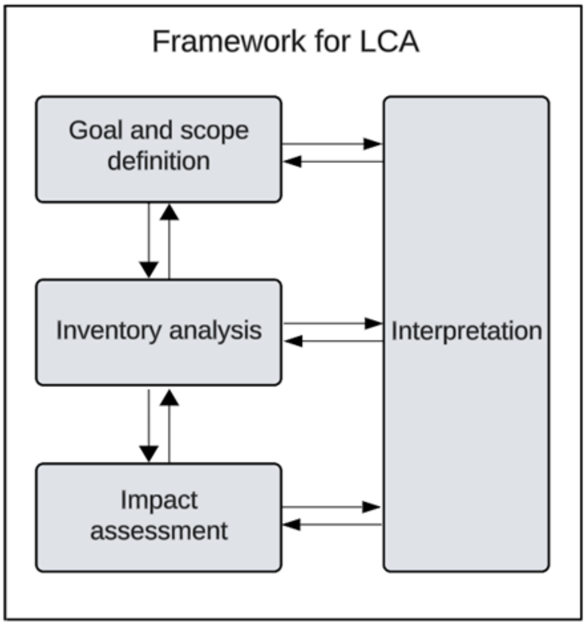


Figure 3.5: Four stages of an LCA.
(Source: ISO, 2006)

3.3.1 Goal and scope definition

The first step in performing an LCA is defining the goal and scope. The goal outlines the reasons for carrying out the study, the intended audience and intended contribution. The scope definition involves defining the product system, system boundaries, functional units, and impact categories to be studied (European Commission. Joint Research Centre., 2019). The goals and a part of scope (system boundaries) of this LCA are already explained in section 3.1 and in figure 3.1. The primary audiences for this study include policymakers, garment manufacturing industries, the academic community, product designers and businesses involved in the disposal, sorting and recycling of textile waste.

Functional unit

A functional unit (FU) is a measure that captures the function of the product system, serving as a reference for assessing environmental impacts and facilitating comparison between alternative systems (ISO, 2006). In this study, the functional unit is defined as the 'use of two t-shirts', allowing for the evaluation of environmental burdens of two t-shirts, regardless of their composition - whether primary or recycled materials. Each t-shirt is assumed to be used at the consumer level, weighing 110 grams, and being white without any prints and trimmings, consistent across both lifecycles as illustrated in figure 3.2. As discussed in section 3.2.1, specifications of the t-shirt, such as garment weight, color, and production inventories, are adopted from the study by Sandin, Roos, et al. (2019). However, further details such as garment size and gender are not specified in the paper.

Impact comparisons will be conducted within individual case studies, not between them, ensuring a focused analysis on material-specific impacts. This approach aligns with the study's purpose, which is not to compare cotton and polyester to determine which is better, but rather to compare the environmental impact of two primary cotton t-shirts with that of a pair, where one is made of primary cotton and the other features recycled cotton recovered from a previously used t-shirt.

3.3.2 Life cycle inventory (LCI)

In the LCI phase of the LCA, inputs and outputs are quantified for every process involved in the product's life cycle (ISO, 2006). This section discusses the approaches and sources used to model unit processes within the system boundary for this study. For each unit process, the input of material and energy is considered per unit of output. The resulting impact per unit process is then incorporated with the quantified outflows of that particular process found in the MFA studies. The system boundaries shown in figure 3.1 represent the foreground unit processes, while background unit processes, including raw materials, energy, and water inputs, as well as emissions to air, water and soil, are also incorporated. Due to the unavailability of production and recycling related inventory data for specific geographical locations, common inventories related to these stages were collected from literature review and utilized in this thesis. When selecting geographic options from Ecoinvent background processes, the location assumptions from section 3.1 were preferred. However, in most cases, geographic location was chosen as 'market activity' for global (GLO) or rest-of-the-world (RoW) due to the lack of available background data for specific locations. For example, a dataset for the 'treatment of municipal solid waste' specific to the

Norway region was used for modelling incineration in Norway. But, no specific dataset for China was available, so global (GLO) average was selected for modelling waste treatment in China.

Table 3.3: Foreground processes and their main data sources.

Foreground process	**Main sources**
Fibre production (China)	Ecoinvent 3.8
PET production (China)	Ecoinvent 3.8
Yarn production (China)	Sandin, Roos, et al. (2019), Moazzem, Crossin, et al. (2021)
Fabric production (China)	Sandin, Roos, et al. (2019), Alam et al. (2023)
Wet processing (China)	Sandin, Roos, et al. (2019), Alam et al. (2023)
Apparel production (China)	Sandin, Roos, et al. (2019), Alam et al. (2023))
Distribution (China-Norway)	Google Maps (n.d.) & Sea-Distances.org (n.d.)
Use phase (Norway)	Sandin, Roos, et al. (2019)
Residual waste collection (Norway)	Mora-Sojo et al. (2023), Lausselet et al. (2016)
Incineration (China/Norway/Lithuania)	Mora-Sojo et al. (2023), Lausselet et al. (2016)
Separate collection (Norway)	Schmidt et al. (2016), Mora-Sojo et al. (2023)
Sorting (Lithuania)	Nørup et al. (2019)
Recycling (China)	Schmidt et al. (2016)
Re-granulation (China)	Ecoinvent 3.8

Data collection

This study relies on a comprehensive literature review for modeling foreground unit processes. Table 3.3 represents the main data sources used to model these processes. For all background processes and some foreground processes, Ecoinvent v.3.8 datasets were utilized. Although Sandin, Roos, et al. (2019) is the primary source for developing foreground processes related to the production phase, the fibrous material waste in different processes observed in their study was very low or nonexistent compared to other studies. These other studies used primary data from manufacturing factories (Alam et al., 2023, Khairul Akter et al., 2022) or secondary data from various sources (Moazzem, Crossin, et al., 2021). For instance, Sandin, Roos, et al. (2019) did not account for any fabric waste in wet processing, whereas Alam et al. (2023) reported a fabric loss of around 11% in wet processing, and Moazzem, Crossin, et al. (2021) reported this loss ranging from 3% to 10%. These process losses are relevant for both LCA and MFA (as shown in table 3.2) in this study.

Unit processes

This section provides a detailed description of the foreground unit processeses and the assumptions underlying their modelling in the LCA study. Pre-consumer waste generated at different production stages is modelled as municipal waste treatment (i.e., incinerated) to simplify the model and account for uncertainty regarding the fate of these wastes, as discussed in section 2.1.2. To model transportation between production facilities, this study adopts an assumption from Dinkel et al. (2007), which considers 250 km transport distance by lorry for each movement from one production process to the next in China. Therefore, a 250 km transport distance is added to yarn, fabric, dyeing, apparel production and recycling processes modelled in China.

For the recycling product system in this study, it is assumed that all production stages from yarn production to apparel production and the use phase of t-shirt 2, will follow the same unit processes developed for t-shirt 1. This assumption is made due to a lack of evidence regarding distinct production process for recycled content. For example, there is no research found indicating that spinning recycled yarn or wet processing of recycled fabric requires more or less energy or material. However, this information is critical for the comparative LCA study between linear and recycling product systems. This uncertainty will be further discussed in section 5.4. Moreover, in addition to the following subsections, further details on modelling unit processes are added in section 7.1 in the appendix.

Fictional electricity mix used in production

Electricity is another common inventory used in many foreground processes within the system boundary. Country-specific electricity mixes were used for modelling pre-sorting, sorting and recycling processes. For production stages from yarn production to apparel production, where the majority of electricity is required, a fictional electricity mix was used instead of China's electricity mix. This fictional electricity mix is developed based on the share of net import value from different clothing manufacturing countries to Norway in 2018. Table 3.4 shows the share of net import value for clothing in 2018 according to World Bank (2021) and the datasets used for each country's electricity mix from Ecoinvent. Producing countries contributing at least 3% of the total import were included in table 3.4. It is observed that 64% of total import came from seven countries, with the remaining 36% coming from other countries. To develop the fictional electricity mix, this 36% contribution was redistributed among the top seven exporting countries proportionally. The purpose of this fictional electricity mix is to provide a more accurate estimate of the impact for electricity, as emission intensities vary between countries. Using only China's electricity

Table 3.4: Import data for generating fictional electricity mix.

Manufacturing country	**Net import (US$ Thousand)**	**Import share%**	**Modelled share of Electricity mix%**	**Ecoinvent dataset for fictional electricity mix**
China	1,181,008	35%	55%	market group for electricity, medium voltage, CN
Bangladesh	257,844	8%	12%	market for electricity, medium voltage, BD
Turkey	203,387	6%	9%	market for electricity, medium voltage, TR
India	166,277	5%	8%	market group for electricity, medium voltage, IN
Germany	129,268	4%	6%	market for electricity, medium voltage, DE
Vietnam	113,065	3%	5%	market for electricity, medium voltage, VN
Italy	108,795	3%	5%	market for electricity, medium voltage, IT
Others	1,219,956	36%	0%	
Total	3,379,603	100%	100%	

mix could result in an overestimation or underestimation of the environmental impact.

Fibre production

Cotton is a natural fibre extracted from cotton seeds. Cultivation of cotton requires substantial water from irrigation and precipitation, along with fertilizers, herbicides, pesticides, and land occupation (Esteve-Turrillas and De La Guardia, 2017). Following harvesting, the ginning process separates cotton lint from seeds and other residues. Cotton staple fibres are then baled and sent to spinning mill for yarn production. This thesis uses Ecoinvent dataset for modeling this process, which incorporates all production stages, including cultivation, ginning, transportation to the yarn mill and process losses.

Polyester is a synthetic fibre commonly produced from fossil-based raw materials like dimethyl terephthalate (DMT) and ethylene glycol (EC) (Sandin, Roos, et al., 2019). These monomers undergo polymerization to form polyethene terephthalate (PET) polymers, which are then cooled and cut into granulates or pellets. These granulates are re-melted and extruded through spinnerets to form polyester filament fibres. The fibre length of polyester filament yarn can be controlled because it is a man-made process, whereas the fibre length in natural staple fibre like cotton is generally shorter and varies naturally (Sandin, Roos, et al., 2019). Ecoinvent datasets were used for both modelling polyester fibre and PET polymer production. Based on the Ecoinvent dataset, waste generated in polyester fibre production, primarily plastic waste, was estimated at 1.4%. Since the transport of fibre was not included in the dataset, it was added in the next process i.e., polyester yarn production.

Yarn production

Yarn production for cotton and polyester involves several steps, including carding, combing, drawing, roving, spinning and twisting (European Commission. Joint Research Centre., 2023). Cotton yarn production starts with opening the bales from harvesting, followed by carding to remove short fibres and impurities, and combing to further eliminate short fibres to produce high-quality yarn, whereas polyester filament yarns are produced through texturing, drawing, twisting and winding (Sandin, Roos, et al., 2019).

Sandin, Roos, et al. (2019) considered 169 dtex (a measure of thickness) cotton yarn for a 100% cotton t-shirt, but they used 119 dtex polyester yarn for another type of garment that was not a t-shirt and did not weigh 110 grams. But in this thesis, different thicknesses of yarn were used: 169 dtex for cotton and 119 dtex for polyester, to make cotton and polyester t-shirt of the same weight, 110 grams. This assumption was made due to a lack of specific references for the exact count or thickness of polyester yarn required for a 110-gram polyester t-shirt. Yarn thickness is important because energy consumption for yarn production depends on it, thicker yarns (higher dtex) require less energy. Therefore, this thesis potentially overestimates the energy consumption for polyester yarn production, as 119 dtex yarn uses more energy than 169 dtex yarn. Waste generated in this process includes short fibres, damaged yarn, and quality-failed yarn (Khairul Akter et al., 2022).

Fabric production

T-shirts are typically made of knitted fabric, produced by circular knitting machine that inter-loops yarn to create fabric. Average energy consumption for both cotton and polyester fabric production is considered to be 0.5 kWh per kg of yarn, with a waste percentage of 2% based on Alam et al. (2023). This waste includes leftover yarn and rejected fabric of poor quality (Khairul Akter et al., 2022).

Wet processing

Wet processing of knit garments includes pre-treatment, dyeing and finishing. Pre-treatment involves bleaching to improve subsequent dyeing. Cotton is dyed with reactive, vat or direct dyes, while polyester is dyed with disperse dyes. After dyeing, finishing involves drying and fixing the fabric's weight and dimension in stenter machine (Sandin, Roos, et al., 2019). Rejected fabric due to quality issues, such as uneven dyeing and unmatched shades, is considered process loss in this process (Alam et al., 2023).

Apparel production

Apparel production involves cutting finished fabric into different body parts, sewing these parts into garments, and then ironing and packaging the ready-made garments. Waste generated includes rejected cut panels and complete garments with sewing defects (Alam et al., 2023).

Distribution

After the manufacturing, garments are assumed to be shipped from China to Norway. Rough assumptions were made about the ports used, distance and transport vehicles. Table 3.5 shows the assumptions made in modelling the distribution with 1% waste considered in this process due to unsold garments at selling stores, based on Sandin, Roos, et al. (2019).

Table 3.5: Transport distances used in modelling distribution process.

From - To	Distance	Source
Mock factory - Shanghai port	250 km	Dinkel et al. (2007)
Shanghai port - Oslo port	20,428 km	Sea-Distances.org (n.d.)
Oslo port - Distribution center	80 km	Rough assumption
Distribution center - Retail store	30 km	Rough assumption

Use phase

Modelling of the use phase considers laundry activities, including washing, drying and ironing. This thesis assumes that Norwegian people have similar buying and usage patterns for t-shirts as Swedes. Sandin, Roos, et al. (2019) estimated that Swedes wear a t-shirt 30 times before discarding it and wash it on average after every 2 uses, based on studies by Granello et al. (2015) and Gwozdz et al. (2013). For simplification, it is assumed that after every wash, the t-shirt will be dried and ironed. The Ecoinvent dataset for 'market for washing, drying and finishing laundry' is used for modelling the use phase. However, consumer mobility to and from stores to buy new t-shirt is not considered in this thesis.

Residual waste collection

After the use phase, t-shirts are discarded either into municipal residual waste or separate collection container. When they end up in residual waste, their final fate is being incinerated (Watson et al., 2020). Modelling of this process includes transport of municipal collection lorries and transport of waste from waste facilities to incineration plants, based on studies by Lausselet et al. (2016) and Mora-Sojo et al. (2023).

Separate collection

In the recycling product system, 60% of the discarded used t-shirts are assumed to be collected separately for further processing. This percentage is adopted from studies by Mora-Sojo et al. (2023) and Watson et al. (2020), which mapped the Norwegian household clothing system for 2018. For modelling separate collection, a transport distance of 150 km by lorry from the collection point to pre-sorting facilities is considered based on Schmidt et al. (2016), which indicated a variation of 10 to 150 km was possible for this distance. Schmidt et al. (2016) also estimated 70 kWh electricity consumption per tonne of pre-sorted garments, which is also adopted in this thesis. Moreover, 1.2% of collected garments are considered contaminated or waste and are sent to incineration (Watson et al., 2020).

Sorting

After separate collection and pre-sorting, garments are assumed to be sent to large-scale sorting center in Lithuania, where they are segregated into reusable, recyclable and waste categories based on their quality. Since this thesis explores system performance based on closed-loop recycling of garments, it is assumed that the share of garments classified as reusable is also suitable for recycling. According to Nørup et al. (2019), 6% of sorted garments are classified as waste, with the remaining portion being either reusable or recyclable. For modelling this unit process, the amount of electricity, heat and bailing wire are considered based on Nørup et al. (2019). Transport was assumed as per the distances provided in table 3.6, for the transport of goods from Oslo to Vilnius, where the sorting center is located.

Table 3.6: Transport distances used in modelling sorting process.

From - To	Distance	Source
Oslo, Norway - Nynäshamn, Sweden	539 km	Google Maps (n.d.)
Nynäshamn port, Sweden - Ventspils port, Latvia	275 km	Google Maps (n.d.)
Ventspils port, Latvia - Vilnius, Lithuania	440 km	Google Maps (n.d.)

Recycling

In this thesis, closed-loop recycling of cotton and polyester garments is considered so that recycled materials can be used in the production of the same types of products. Therefore, mechanical recycling of cotton and chemical recycling of polyester are modelled.

Mechanical recycling of cotton garment involves cutting sorted garments into small pieces using a mechanical shredding machine. These pieces are then processed through a rotating drum to turn them into loose fibres suitable for spinning into cotton yarn (Schmidt et al., 2016). On the other hand, chemical recycling involves cutting the polyester garments, washing them and then dissolving them in an organic compound to undergo depolymerization. This process produces raw materials of polyester yarn, such as dimethyl terephthalate (DMT) and ethylene glycol (EG) (Schmidt et al., 2016). Energy and chemicals used in these mechanical and chemical processes, and process losses are adopted from the same study. Table 3.7 shows the distance covered by sorted t-shirts from Vilnius, Lithuania to a mock recycling factory in China.

Table 3.7: Transport distances used in modelling recycling process.

From - To	Distance	Source
Latvia - Vilnius, Lithuania - Klaipeda port, Lithuania	311 km	Google Maps (n.d.)
Klaipeda port, Lithuania - Shanghai port	21,100 km	Sea-Distances.org (n.d.)
Shanghai port - Mock factory	250 km	Dinkel et al. (2007)

The amount of material recovered from t-shirt 1 will reduce the demand for primary raw material for t-shirt 2 on a replacement rate of 1:1. For example, in the recycling product system, if 50 grams of material are recycled from t-shirt 1, this 50 grams of fibre can replace 50 grams of primary fibre needed for the production of t-shirt 2.

Regranulation of PET

This process is part of the chemical recycling of polyester t-shirt, where the DMT and EG from chemical recycling are turned into polyethene terephthalate (PET) granulates through polymerization. The Ecoinvent dataset for the process of 'polyethylene terephthalate, granulate, amorphous, RoW' is used for modelling this regranulation process. According to ecoinvent dataset, 82.7% of EG and DMT (by weight) are converted into PET granulates, with the remainder considered as waste.

3.3.3 Allocation

Allocation is a method used to distribute environmental impact among different products or processes in a product's life cycle (ISO, 2006). The Allocation at the point of substitution (APOS) method is used for all background flows in this thesis to allocate the environmental burden in a system where waste is generated and can be converted into useful products. When waste is recycled, the APOS method allocates a part of the impact of these processes to the waste-generating activity and the recycled material (Ekvall et al., 2020). This indicates that the burdens of primary production are assigned to the first product and the subsequent recycled product.

3.3.4 Impact categories

Table 3.8 represents the impact categories, methods and corresponding characterization factors included in this study. The cultivation of cotton, use of fertilizers, fossil raw materials, electricity, water and chemicals across the entire supply chain make these impact categories particularly relevant. Also, according to Sandin and Peters (2018) these are the most studied impact categories for textile operations. The Activity-Browser software was used for modelling and impact assessment.

Table 3.8: Studied midpoint impact categories, with their method and characterization factors.

Impact categories	Method	Characterization factor	Unit
Climate change	ReCiPe 2016 v1.03, Midpoint, Hierarchist	Global warming potential (GWP100)	Kg CO_2-eq
Ecotoxicity	USEtox	Ecotoxicity potential	CTU
Land use	ReCiPe 2016 v1.03, Midpoint, Hierarchist	Agricultural land occupation (LOP)	m^2.yr cropland-Eq
Water use	ReCiPe 2016 v1.03, Midpoint, Hierarchist	Water consumption potential (WCP)	m^3
Energy use	Cumulative energy demand (CED)	Energy content (HHV)	MJ - Eq

3.4 Scenario development

This section outlines the development of four alternative scenarios to evaluate the potential of the recycling product system. These scenarios focus on four key parameters within the studied product system: separate collection rate, location of sorting and recycling plants, process loss percentage at production stages, and pre-consumer waste recycling options. The objective is to analyze how variations in these parameters affect material flows and the environmental impact of the system. Table 3.9 summarizes the parameters considered and their values considered in the scenario analysis.

Table 3.9: Parameters considered in alternative recycling product scenarios.

Scenarios	Collection rate%	Location of sorting & recycling	Process loss%	Pre-consumer waste recycling
Default	60%	Lithuania & China	16% - Yarn 11% - Wet processing 15% - Apparel	No
Higher collection	**90%**	Lithuania & China	16% - Yarn 11% - Wet processing 15% - Apparel	No
Local sorting & recycling	60%	**Norway & Norway**	16% - Yarn 11% - Wet processing 15% - Apparel	No
Waste minimization	60%	Lithuania & China	**13% - Yarn** **5% - Wet processing** **10% - Apparel**	No
Pre-consumer waste recycling	60%	Lithuania & China	16% - Yarn 11% - Wet processing 15% - Apparel	**Yes**

Default scenario

Previously developed recycled product system for both cotton and polyester cases is set as the default scenario. As explained in section 3.3.2, the default scenario, considers collection rate of 60%. The sorting and recycling centers are located in Lithuania and China respectively. Process losses at yarn, dyeing and apparel production are considered to be 16%, 11%, and 15% respectively, with waste modelled as being incinerated through municipal solid waste treatment.

High collection scenario

This scenario stems from the EU's waste framework directive, which mandates the separate collection of textile waste by January 1, 2025 (European commission, 2023b). This scenario assumes a 90% separate collection rate, a significant increase from the current 60% level. Despite this, 10% of discarded garments are still expected to end up in residual waste due to factors including consumer behavior, available infrastructure, and enforcement of regulations. For example, although EU member countries are expected to activate separate collection of textiles by 2025, there are concerns about the readiness of infrastructure for collection, sorting and recycling facilities (European commission, 2023a). Additionally, consumer behavior regarding waste separation is influenced by factors such as previous habits, convenience, social influence, and demographics (Xu et al., 2017).

Local post-consumer waste sorting and recycling scenario

In this scenario, large-scale sorting center and recycling facilities are assumed to be located in Norway instead of Lithuania and China, as in the default scenario. This change is based on the European commission's expectation that sorting will occur in most member countries and on a large scale where market conditions are favorable, such as lower management costs, upscalable infrastructure, and the potential to become a regional recycling hub (European commission, 2023a). The chosen location for this scenario is Sandefjord, where a Norwegian textile-to-textile recycling factory is already located. This adjustment will impact transport distances from the pre-sorting center to sorting center and the electricity country mix used in recycling facilities compared to the default scenario.

Waste minimization scenario

During the modelling of unit processes, it was observed that yarn production, wet processing, and apparel production are the processes that generate the most waste. Studies by Moazzem, Crossin, et al. (2021) and Alam et al. (2023) provided a range of process losses for these activities. Average or frequently observed values from survey were considered in the default scenario. However, this scenario evaluates the impact of using the minimum value of the process loss range on material flows and environmental impact. It is important to note that the process loss at yarn production for polyester is 4% due to its synthetic nature and more controlled production process, with no significant variations observed in studies. Thus, it has been kept the same across scenarios. Therefore, for the polyester case, only the values for wet processing and apparel production parameters were adjusted to assess the impact of minimizing process loss.

Pre-consumer waste recycling scenario

Currently a significant share of the pre-consumer waste is managed by the informal market, as discussed in section 2.1.2. This scenario assumes that pre-consumer waste will be recycled in the manufacturing country, China, instead of being incinerated as in default scenario. This assumption is based on new regulations, infrastructure development, and concerns raised in manufacturing countries to manage the substantial amount of pre-consumer waste generated annually (Khairul Akter et al., 2022, Li et al., 2021).

3.5 Evaluating country-wide impact

To contextualize the product-level LCA on a broader scale, this study attempted to evaluate the potential environmental savings if Norwegian household t-shirt consumption follows the recycling product system instead of the linear product system. This evaluation is conducted in three steps:

1. Determine consumption of new t-shirts by Norwegian households.
2. Divide consumption into two groups.
3. Evaluate environmental benefits.

The consumption of new t-shirts by households in 2018 was determined using the following equation:

Consumption of new t-shirts = Import of t-shirts − Export of t-shirts

The UN Comtrade database (*UN Comtrade* 2020) was utilized to obtain export and import data for t-shirts, classified under combined nomenclature (CN) code 610910 for cotton t-shirts and CN code 610990 for 'other than cotton' t-shirts. For this analysis, 'other than cotton' t-shirts are assumed to be polyester t-shirts, as cotton, and polyester and cotton/polyester blends are the most common compositions for t-shirts (Superior ink, 2024).

The total consumption of new t-shirts was then divided into two equal groups: group 1 and group 2. The purpose of this grouping is to align with previously developed MFA models, as shown in figures 3.3 and 3.4. Group 1 and group 2 will correspond to t-shirt 1 and t-shirt 2 in the linear and recycling product systems. Since the data pulled from UN Comtrade reflects the annual consumption of new t-shirts for 2018, dividing the total consumption into two groups represents half-yearly consumption. Hence, this hypothetical analysis aims to determine the potential amount of recovered materials and environmental benefits if half-yearly discarded t-shirts are recycled and the recycled materials are used in the production of the second half of the yearly consumption.

The functional unit for this analysis is defined as the ‘consumption of t-shirts over a year by Norwegian households’. While previous product systems considered the t-shirts to be white, the annual country-wide consumption includes various colors, and additional variabilities such as prints and trimmings. To avoid complexity in the model, the aspect of t-shirt color and other variabilities are ignored. Additionally, a small portion of online shopping from abroad (4%) and domestic production (3%) of garments, as reported by Watson et al. (2020), also account for the consumption of new garments. These portions are not reflected in the estimation of t-shirt consumption based on the CN codes.

3.6 Uncertainty analysis

In developing the MFA models and performing LCA, several assumptions were made due to data unavailability or to reflect the average or commonly observed data. These assumptions introduce uncertainties in system performance, making sensitivity analysis crucial to assess the reliability of results under such uncertain factors.

Table 3.10 represents the key uncertain parameters in the model, their average values used in the default recycling product systems and their ranges (maximum and minimum) tested in sensitivity analysis. In this study, sensitivity analysis included five parameters: process loss percentages in yarn production, wet processing, apparel production, mechanical recycling, and energy input for chemical recycling. As discussed in the ‘waste minimization scenario’ in section 3.4, significant amount of waste generated in spinning, dyeing and sewing stages, and researchers observed a range of process loss percentage across surveyed production plants. For mechanical and chemical recycling, this thesis adopted process efficiency from a single study due to unavailability of other data sources. Schmidt et al. (2016) provided inventory data from two pilot projects and highlighted the uncertainty of these data, especially regarding energy input for chemical recycling. Since Schmidt et al. did not specify any uncertainty range, an uncertainty range was decided based on the judgement of the author of this thesis.

Table 3.10: Key parameters and their upper and lower limits for sensitivity analysis.

Parameters	**Parameter value used in default recycling product systems**	**Uncertainty range and comments**
Process loss% in yarn production	16%	Based on Alam et al. (2023) and Moazzem, Crossin, et al. (2021), process loss at surveyed factories ranges from 13% to 20%.
Process loss% in wet processing	11%	According to Alam et al. (2023) , process loss at surveyed factories ranges from 3% to 15%.
Process loss% in apparel production	15%	Alam et al. (2023) found process loss at surveyed factories ranges from 10% to 20%.
Process loss% in mechanical recycling	20%	Schmidt et al. (2016) did not share specific data on the quality of garments under recycling. Process loss can vary based on garment type, color, weight, and effectiveness of the recycling technology used. The range for this parameter is considered as 15% to 25%.
Energy use in chemical recycling	Thermal energy from light fuel oil - 13.80 MJ, Thermal energy from natural gas - 3.46 MJ	Schmidt et al. (2016) highlighted the poor data quality regarding thermal energy consumption in the recycling process. Since this is an energy intensive process, a variation of ±25% is considered, so tested ranges are 10.35 - 17.25 MJ for light fuel oil and 2.59 - 4.33 MJ for natural gas.

4 Results

This section presents the results of the study, comparing the linear product system and recycling product systems across five different scenarios. First, section 4.1 details the results from the material flow analysis (MFA) to outline the material flows across the supply chain. Next, section 4.2 presents the environmental impacts calculated by the life cycle assessment (LCA). Section 4.3 provides an estimation of material flows and environmental impacts in the context of Norwegian t-shirt consumption. Finally, results from the uncertainty analysis are presented in section 4.4.

4.1 Material flow analysis

4.1.1 Cotton case

Figure 4.1 shows the MFA for the **linear product system** for the cotton case. The lifecycle of t-shirt-1 starts with an input of 178 grams of cotton fibre into the yarn production. Yarn production yields 150 grams of yarn, with 29 grams of material lost as damaged yarn, short fibres, and quality-failed yarn. The next step is fabric production, which converts the yarn into 147 grams of undyed (greige) fabric, with 3 grams lost as fly fibres, scrap yarn and rejected fabric.

Subsequently, 147 grams of greige fabric undergoes wet treatment with bleaching and whitening agents to become white fabric, which is then fixed with a stenter machine, resulting in 16 grams of material waste. This waste includes unfinished, unevenly dyed fabric, and fabric that does not meet quality standards. Apparel production uses this finished fabric to make the final product by cutting, sewing, and finishing. This stage generates the second highest amount of waste among all production stages after yarn production, with 20 grams of material becoming waste mainly due to inefficiencies during the fabric cutting.

Pre-consumer waste generated during the yarn production, fabric production, wet processing and apparel production, amounting to 68 grams, is sent to municipal waste incineration plants in China for waste treatment. Once t-shirt 1 is made and distributed to Norway, 110 grams reaches to consumer, with 1 gram of waste as unsold product at stores. After the use phase, the entire t-shirt is discarded into municipal residual waste and incinerated at a Norwegian municipal waste incineration plant. Together with all the waste generated at different production stages, the total incinerated material amounts to 178 grams, indicating no accumulation or stock change in the system. T-shirt 2 followed the same process routes of processes with the same amount of materials, resulting in a total of 356 grams of primary fibres entering the system and exiting as incinerated materials over the two consecutive lifetimes of the two t-shirts.

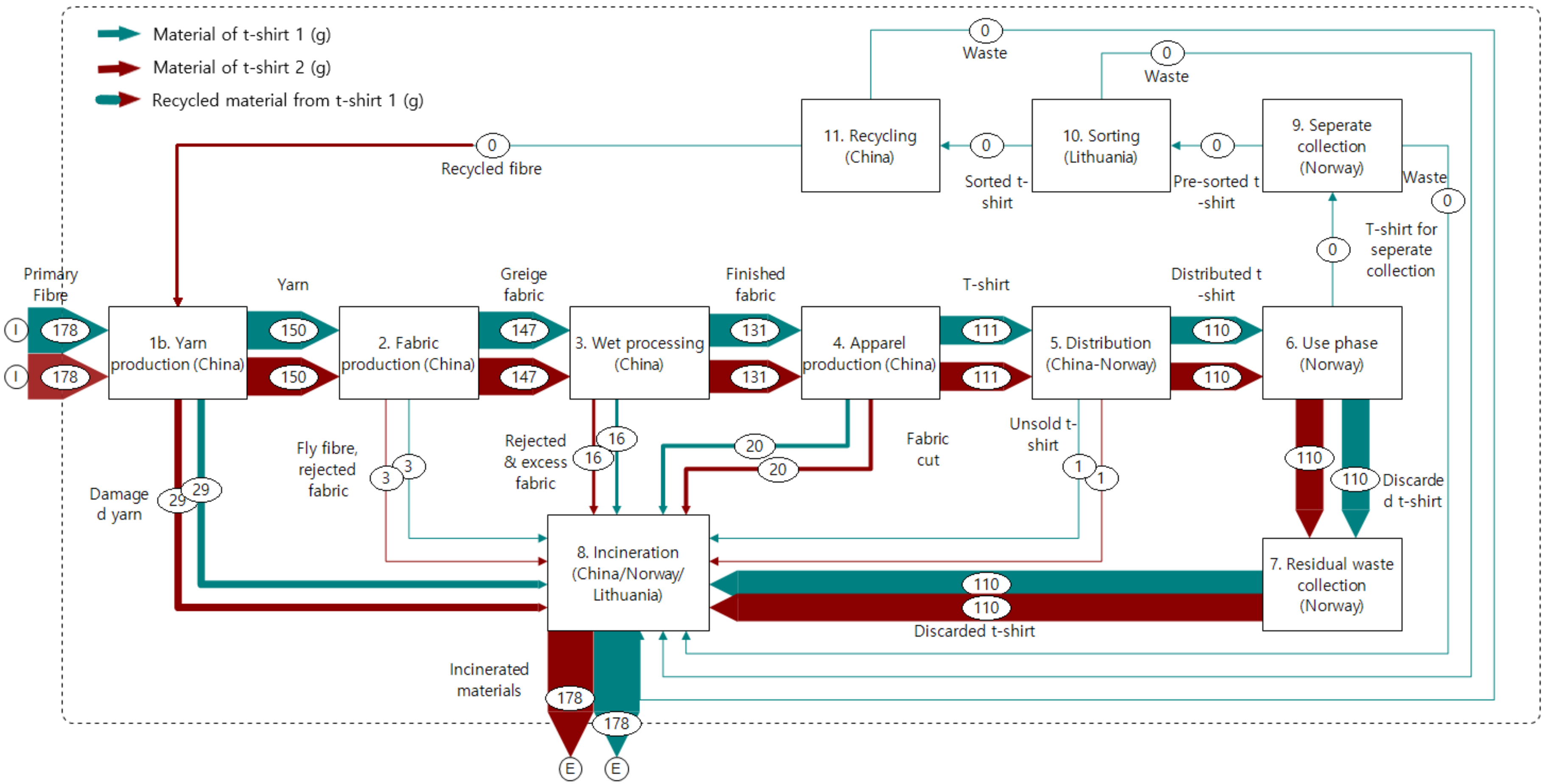


Figure 4.1: Material flows of two t-shirts over two consecutive lifecycles in the Cotton linear product system.

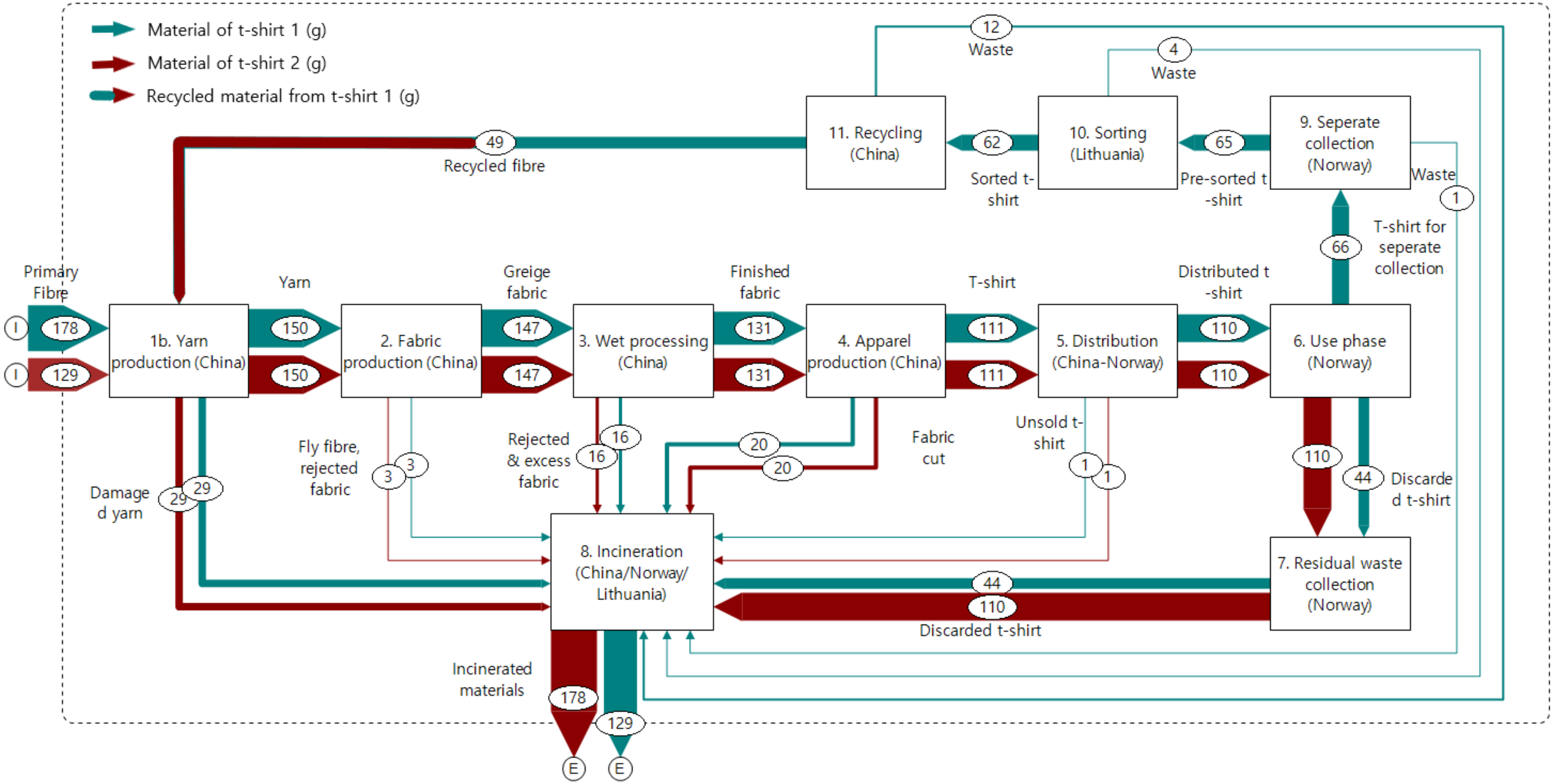


Figure 4.2: Material flows of two t-shirts over two consecutive lifecycles in the Cotton recycling product system.

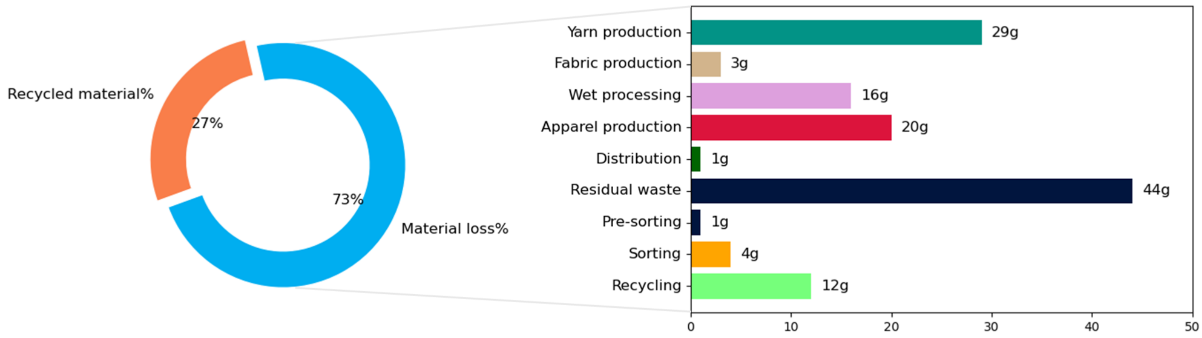
In the **recycling product system**, as shown in figure 4.2, the process similarly starts with 178 grams of cotton fibre for t-shirt 1. The difference compared to the linear system begins after the use phase, where 60% of the t-shirt, amounting to 66 grams, is collected by separate collectors while 44 grams are discarded as residual waste and incinerated in Norway. The collected 66 grams of t-shirt 1 are pre-sorted and sorted, with 5 grams of the materials deemed unsuitable for recycling and thus considered waste. Waste from the pre-sorting center is incinerated in Norway, while waste from the Lithuanian sorting center is incinerated in Lithuania. Ultimately, 49 grams of fibre are recycled and reintroduced into the production of t-shirt 2. During the recycling process 12 grams of material are wasted and incinerated. Comparing the amount of recycled materials to the initial amount of fibrous materials required to manufacture t-shirt 1, the recycled fibre accounts for 27% of the initial primary materials.

The production of t-shirt 2 begins with the spinning of recycled fibres from t-shirt 1, supplemented with the necessary amount of primary fibres. The remaining processes and material flows mirror those in the linear product system, with t-shirt 2 also discarded as residual waste at the end of its use phase. Including both t-shirts, total material input and output are 307 grams, following the mass balance principle.

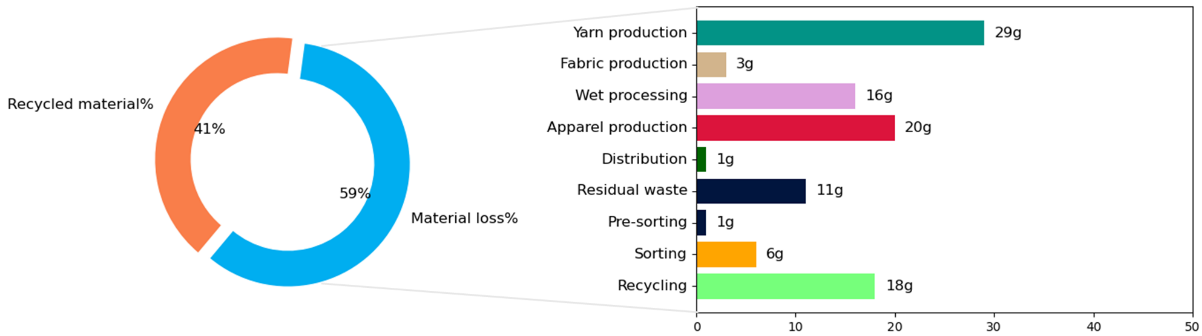
Scenario analysis

Figure 4.3 summarizes the portion of material recycled and lost as waste across the supply chain for t-shirt 1, shown by a pie chart, and the contribution to this loss by each process, illustrated by a bar chart, for four recycling product system scenarios: default, higher collection, Waste minimization, and pre-consumer waste recycling. Overall material loss percentages or recycled percentages are calculated based on the initial material required to produce a t-shirt.

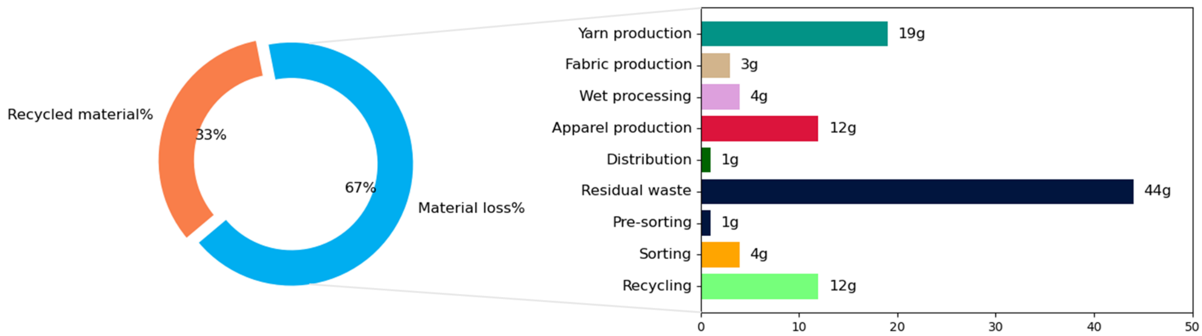
Default scenario: As shown in figure 4.3(a), when the cotton fibre is made into a ready t-shirt, about 38% of the material compared to the initial fibre amount is already lost, including losses at yarn production, fabric production, wet processing and apparel production stages. The largest loss occurs when the garment is discarded into residual waste, with about 25% of the materials ending up in residual waste and destined for incineration. Mechanical recycling of cotton accounts for a 7% material loss. About 73% of initial material is lost throughout the processes, leaving only 27% to be recycled and reintroduced into the production of a new garment. Considering a 1:1 replacement ratio, 49 grams of recycled fibre will reduce the demand for primary fibre by 49 grams for another t-shirt of the same quality.



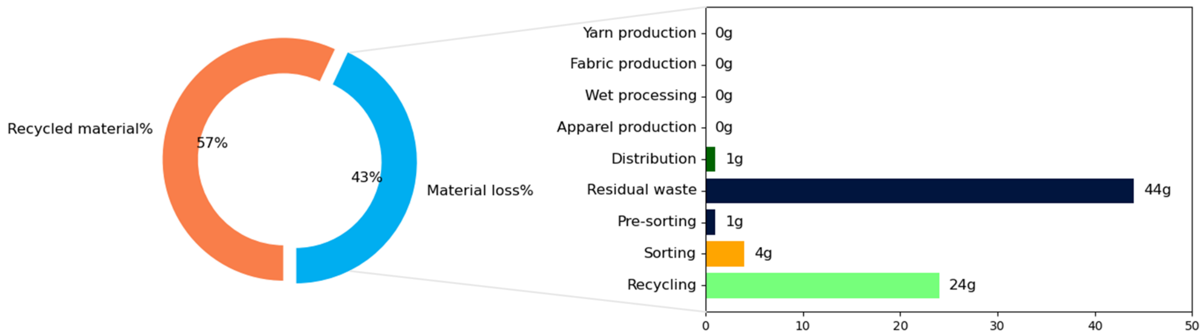
(a) Default scenario



(b) Higher collection scenario



(c) Waste minimization scenario



(d) Pre-consumer waste recycling scenario

Figure 4.3: Material utilization for t-Shirt 1 in cotton recycling product system: Loss vs. Recycled content [(a) Default, (b) Higher Collection, (c) Waste minimization and (d) Pre-consumer waste recycling scenarios]

Higher collection scenario: As shown in figure 4.3(b), material loss during the production phase remains the same. However, due to the increased separate collection rate assumed in section 3.4, material loss in residual waste is reduced to 6% compared to 25% in the default scenario. Higher collection rates lead to slightly more waste in downstream operations compared to the default scenario, with 24 grams of material wasted in sorting and recycling stages. At the end of its lifetime, 41% of the materials can be recovered as recycled fibre, reducing the primary fibre requirement for t-shirt 2 to 105 grams, which is 74 grams less than for t-shirt 1.

Waste minimization scenario: In this scenario, overall 16% less fibre is required to make a t-shirt due to reduced material loss in spinning, wet processing and apparel production, as shown in figure 4.3(c). Material loss in other processes remains the same as in the default scenario. The fibre requirement for making a t-shirt decreases from 178 grams in the linear or the default recycled product system to 149 grams in the waste minimization scenario. Although the same amount of fibres, 49 grams, is recycled in both this and the default scenario, the pie chart shows 33% of the material being recycled compared to 27% in the default scenario.

Pre-consumer waste recycling scenario: In this scenario, waste generated in the production process is sent to recycling instead of being incinerated, while other parameters remain the same as in the default scenario. This scenario allows for the maximum recovery of fibres, with 57% of the materials, or 103 grams, recovered by the end of t-shirt 1's lifecycle. Due to the high material input to the recycling process, the material loss is also higher, maintaining the same 90:10 ratio of recycled fibre to waste.

4.1.2 Polyester case

The quantified linear product product system for polyester is shown in figure 7.5 in the appendix. Unlike the cotton case, which begins with yarn production, the system starts with the fibre production process. Here, 158 grams of primary polyethylene terephthalate (PET) granulates are fed into fibre production to produce polyester yarn, with 2 grams lost as plastic waste. Polyester yarn production generates significantly less waste compared to cotton yarn production, with only a 4% material loss compared to 16% in the cotton process based on Moazzem, Crossin, et al. (2021). Consequently, the initial material requirement for PET granulates is lower than for cotton fibres. Thus, 150 grams of PET granulates enter the system boundary compared to 178 grams of cotton fibre. Following fibre production, the subsequent processes experience the same percentage losses as in the cotton case. However, because the initial amount of PET is different, the actual amount of material lost differs from the cotton case. Apparel production is the most waste-generating stage in the production of a polyester t-shirt. After t-shirt 1 is discarded as residual waste and incinerated, t-shirt 2 follows the same process flows with the same material quantities. Including both t-shirts, a total of 316 grams of primary PET granulates enter the system and the same amount of materials are incinerated across its supply chain and leave the system.

Figure 4.4 illustrates the **recycled product system** for the polyester case. After fibre production, the processes are identical to those in the cotton recycled product system until the sorted t-shirts reach the Lithuanian sorting center. After sorting, the polyester t-shirt undergoes chemical recycling to produce raw materials for polyester yarn. Here, 61 grams of sorted clothing are treated to produce 55 grams of recycled dimethyl terephthalate (DMT) and ethylene glycol (EG), with an estimated 6 grams of waste considering 10% process loss. Through re-granulation, 46 grams of recovered PET granulates are produced and added to the fiber production for t-shirt 2. This process results in 10 grams of polymer material waste considering a 17% process loss. The 46 grams of recycled PET granulates represents 29% of the total initial PET granulates required for producing a polyester t-shirt.

Scenario analysis

Similar to the cotton cases, in the higher collection scenario, the amount of PET granulates recovered from discarded polyester t-shirt is increased. Here, 43% of primary materials are recycled, while the remaining 57% is lost as waste across the supply chain processes. The waste minimization scenario results in lower primary material demand for both t-shirts due to reduced material loss in wet processing and apparel production. In this scenario, 23 grams lesser primary PET granulates are required to produce a t-shirt. In the pre-consumer waste recycling scenario, pre-consumer waste is chemically recycled instead of being incinerated, allowing 51% of the material to be recycled and reintroduced into the production of T-shirt 2. Figure 4.5 summarizes the recovered and waste materials for t-shirt 1 in the polyester case.

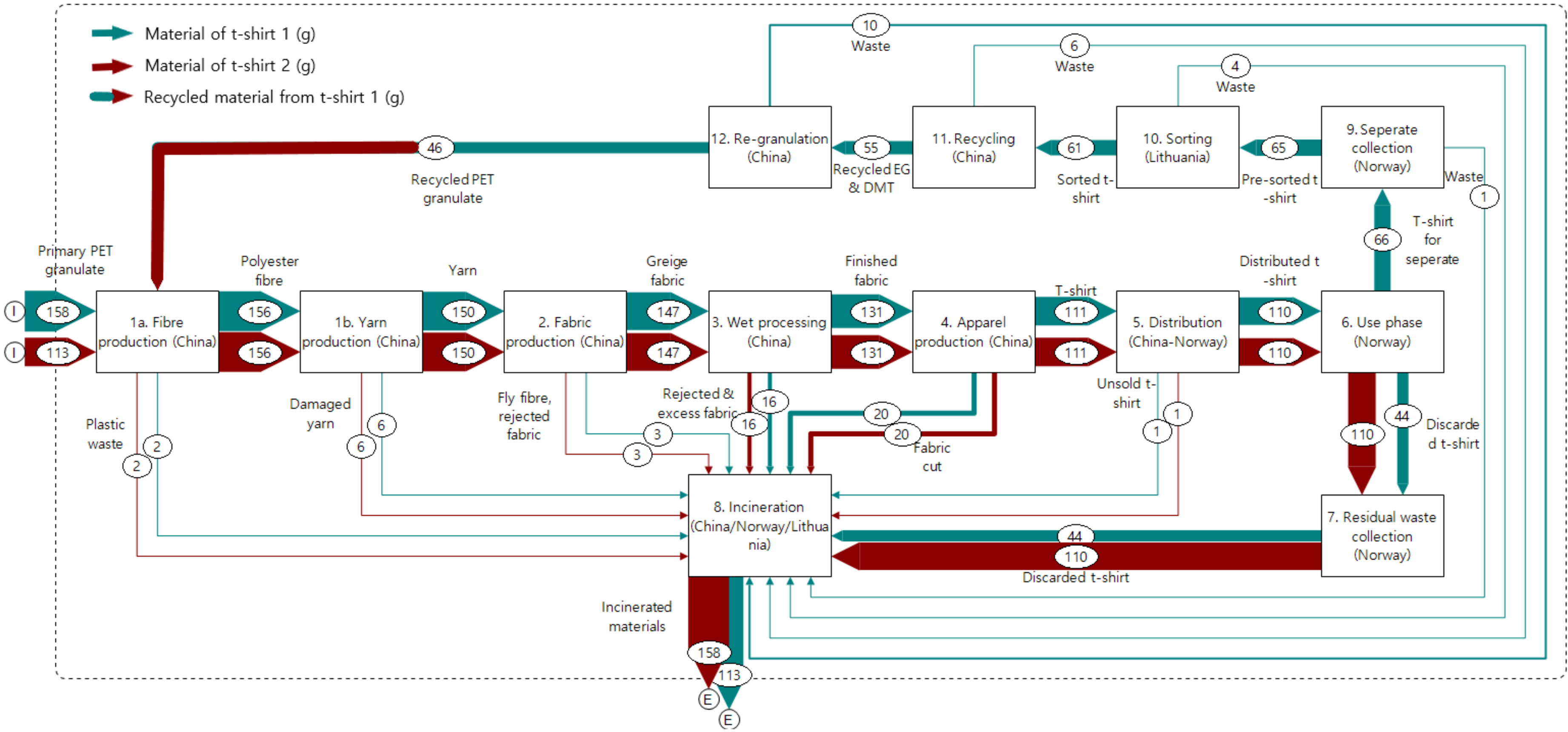
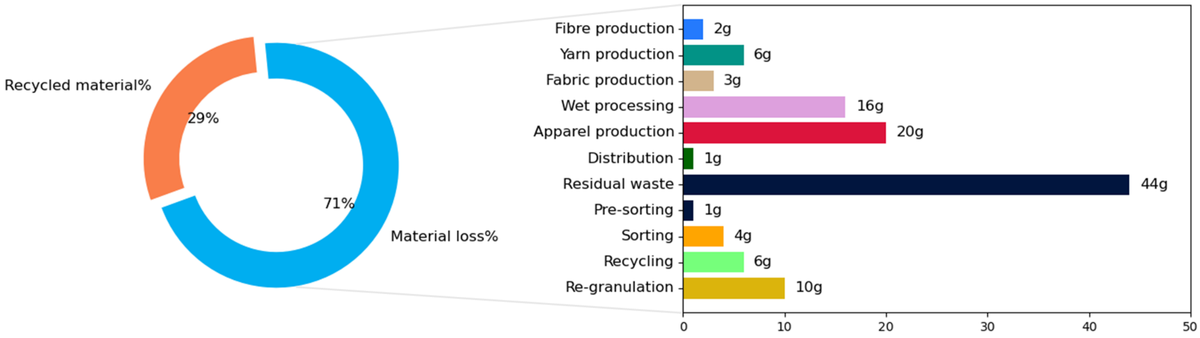
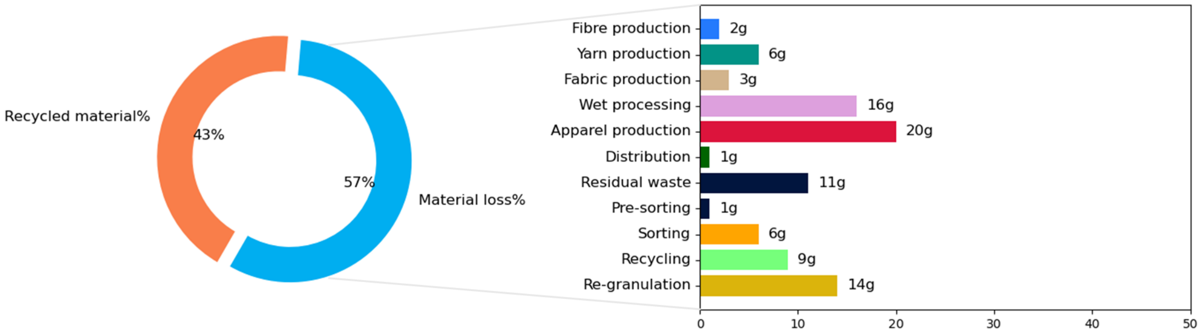


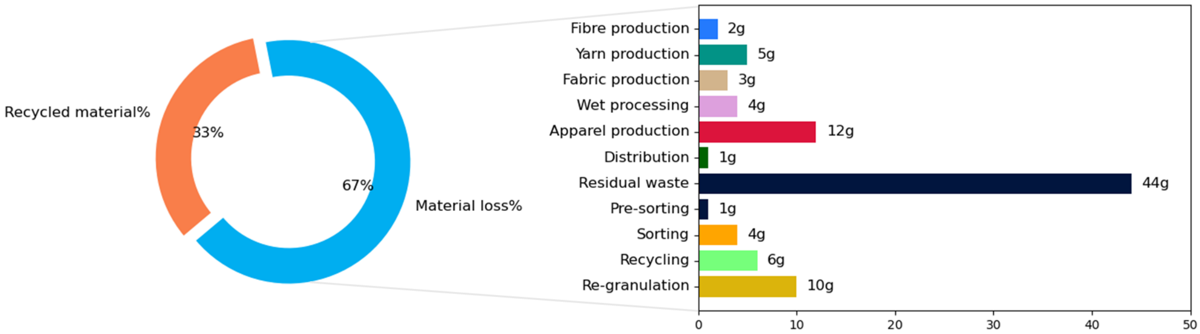
Figure 4.4: Material flows of two t-shirts over two consecutive lifecycles in the polyester recycling product system.



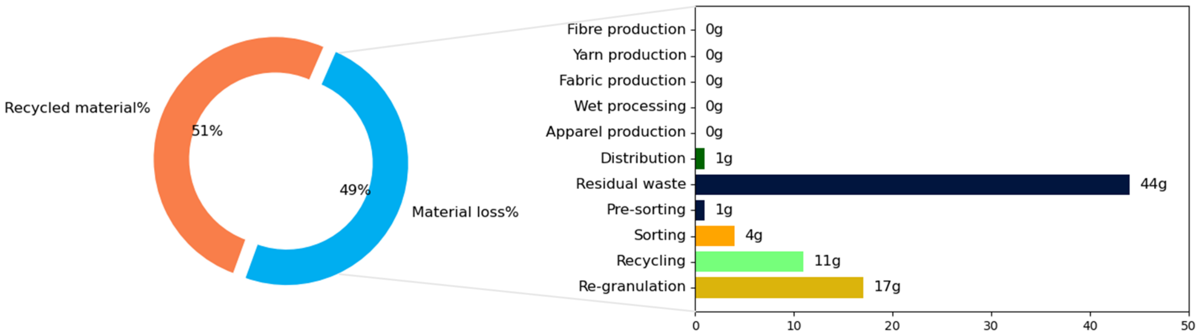
(a) Default scenario



(b) Higher collection scenario



(c) Waste minimization scenario



(d) Pre-consumer waste recycling scenario

Figure 4.5: Material utilization for t-Shirt 1 in polyester recycling product system: Loss vs. Recycled content [(a) Default, (b) Higher Collection, (c) Waste minimization and (d) Pre-consumer waste recycling Scenarios]

4.2 Life cycle assessment

The life cycle impact assessment (LCIA) results for the linear and recycling product systems are presented in this section. Figure 4.6 and 4.13 compare the relative environmental impacts of both systems across five impact categories for cotton and polyester cases, respectively. Each bar represents the total impact, broken down into contributions from different life cycle stages. Combining yarn production, fabric production, wet processing and apparel production into a single category in the bar graph simplifies visualization and highlights the cumulative impact of these production processes.

4.2.1 Cotton case

In the cotton case, the recycling product system shows environmental benefits compared to linear system across all five impact categories. The climate change and energy use impact categories show similar patterns in lifecycle stage contributions. In both categories, operations that convert fibres into ready garments account for more than half of the total impact across the supply chain. These operations collectively result in 3.97 kg CO_2-eq and 53 MJ-eq impacts, with wet processing being the highest impact causing operation, causing 1.84 kg CO_2-eq and 28 MJ-eq, which is more than the impact of cotton production. Following these production processes, activities related to primary fibre production such as cultivation, harvesting, and ginning cause substantial impacts, ranging from 21 to 27% in both impact categories. Laundry during the use phase of the t-shirt, including washing, drying and ironing, is the third highest impact-causing operation for both climate change and energy use.

Unlike climate change and energy use, for ecotoxicity, land use and water use, primary cotton production causes the majority share of the total impact, representing 89% to 94% of the total impacts in these categories. Incineration of t-shirts that end up in residual waste in Norway causes very insignificant impacts across all categories, contributing only 4% to climate change and being negligible in other categories. Interestingly, downstream operations like separate collection in Norway, sorting in Lithuania, recycling in China, those responsible for recycling cotton, contribute less than 1% to the total impacts for all categories. It is essential to examine which background processes contribute to these foreground operations and impact categories within the product systems. The absolute values of these impact categories over two product systems are mentioned in section 7.2 in the appendix.

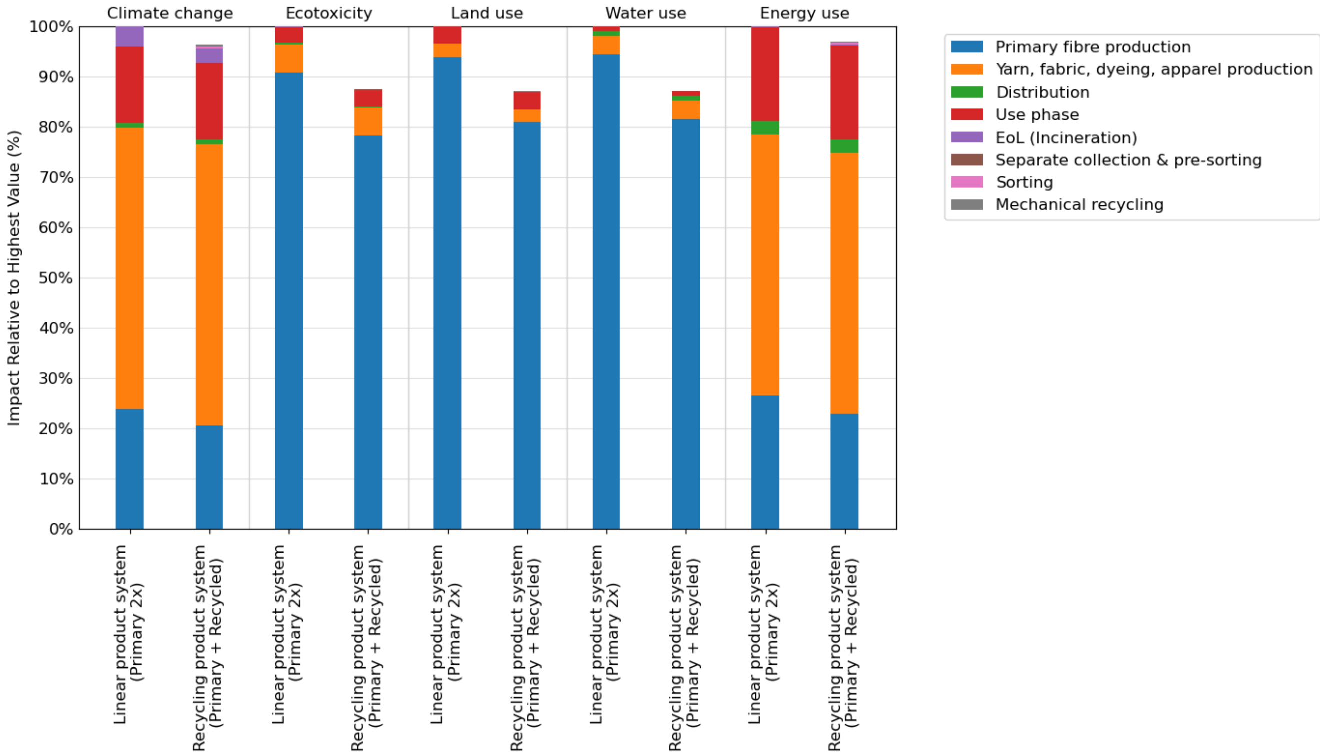


Figure 4.6: LCA results of both linear and recycling product system for cotton case, normalized to the highest impacts per impact category.

Climate change

As shown in figure 4.7, the climate change impact is primarily driven by the use of energy in the form of electricity and heat across the supply chain. Yarn production consumes the most electricity, followed by apparel production and cotton cultivation. Heat is predominantly used in wet processing, where water temperature needs to be raised in the dyeing bath for fabric coloration. Heat is also used in the drying process after washing.

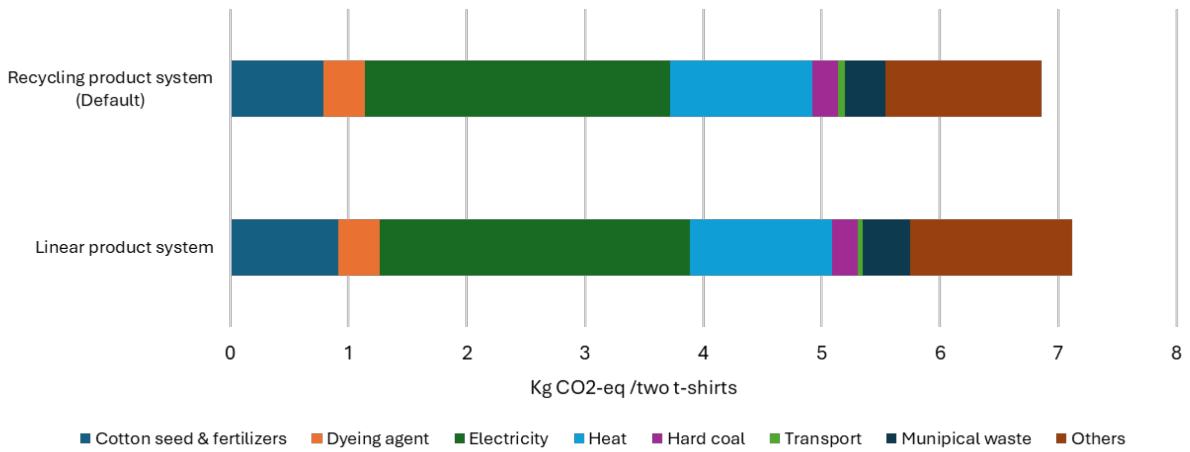


Figure 4.7: Contribution of background processes to climate change impact in cotton case.

Production of cotton seeds, soil ploughing, and fertilizers for cotton cultivation cause around 12% of total impact. The overall impact of the recycling product system is reduced by 0.26 kg CO_2-eq, representing a 3.7% reduction. This decrease is due to factors such as reduced reliance on virgin cotton and a lesser amount of waste incineration at the end-of-life. Conversely, the impact of transportation slightly increases because separately collected t-shirt needs to be transported to sorting center, and then to China for recycling.

Ecotoxicity

Ecotoxicity impact is primarily dominated by the use of cotton seeds during the primary fibre production stage, as shown in figure 4.8. In the linear system, this stage contributes approximately 19 CTUe, while the recycling system shows a slight reduction due to the lower requirement for primary fibres. Wastewater from the dyeing operation also contributes to the total impact, but to a lesser extent. Overall, the recycling system results in a 12% reduction in ecotoxicity impact compared to the linear system.

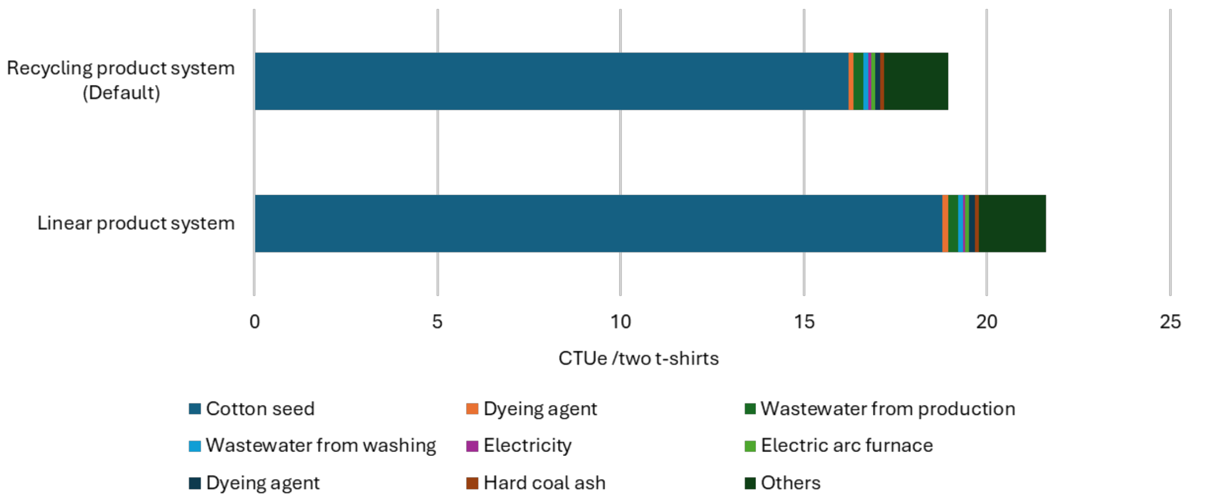


Figure 4.8: Contribution of background processes to ecotoxicity impact in cotton case.

Land use

Similar to ecotoxicity, the land use impact, represented in figure 4.9, is predominantly caused by cotton cultivation. In both systems, cotton seed accounts for around 90% of the total impact. A small portion of the impact is attributed to pulpwood and softwood due to the use of paper in pattern and marker creation for fabric cutting, as well as in carton boxes for packaging. Compared to the linear product system, the recycling system is generating 0.28 m^2*a crop-Eq less impact, representing a 13% reduction.

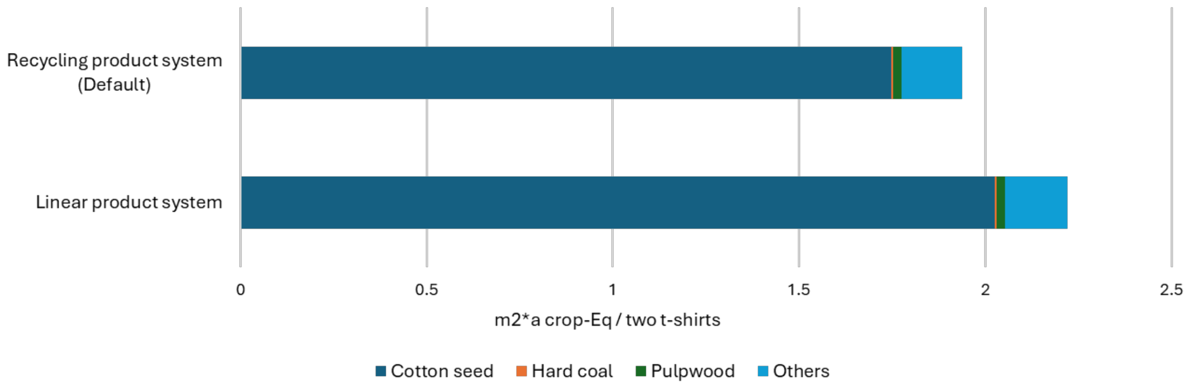


Figure 4.9: Contribution of background processes to land use impact in cotton case.

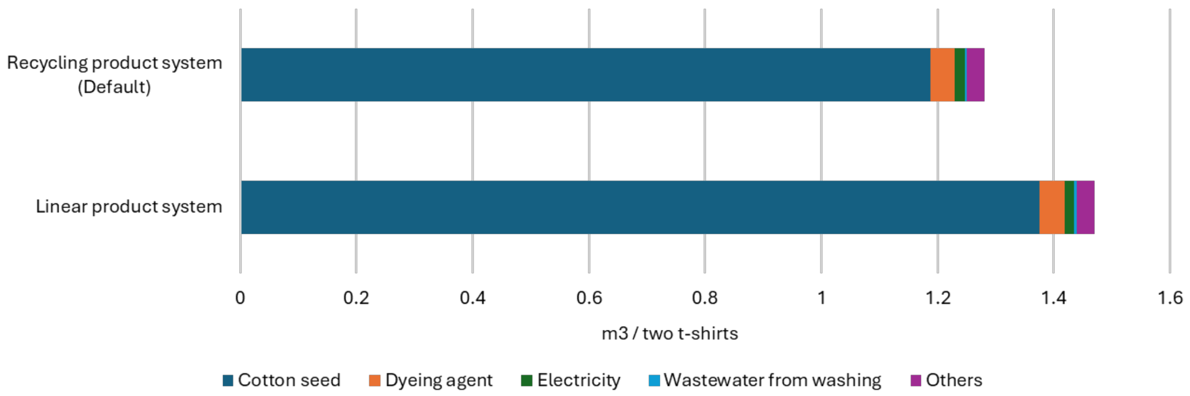


Figure 4.10: Contribution of background processes to water use impact in cotton case.

Water use

The recycling product system causes a water use impact of 1.28 m^3, which is 13% less than that of the linear product system. Cotton seed is responsible for approximately 93% of the water use impact. Dyeing agents used in wet processing and electricity used across all production processes contribute a small amount to this category. Figure 4.10 shows the overview of the contributions.

Energy use

The energy use impact is primarily driven by the use of hard coal and natural gas in the production of electricity across the supply chain. The impact from petroleum mainly arises due to heat generation in the dyeing process. As shown in figure 4.11, the recycling product system results in only a 3% reduction in overall impact compared to the linear system. Cotton seed and dyeing agents together contribute to around 20% of the total energy use impact.

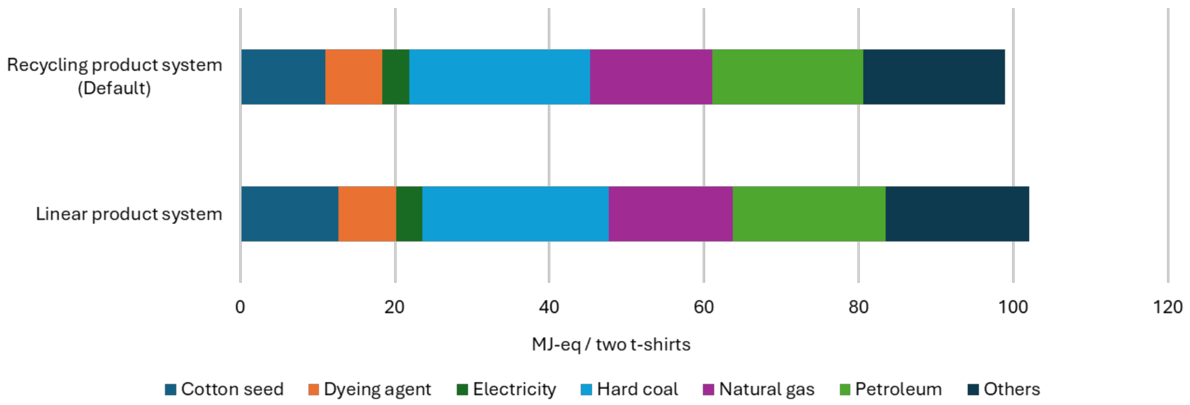


Figure 4.11: Contribution of background processes to energy use impact in cotton case.

Scenario analysis

Figure 4.12 compares the environmental performance of the developed scenarios. the first three recycling scenarios focus on post-consumer waste utilization and are highlighted with teal to cyan colored bars. The last two scenarios address the minimization and utilization of pre-consumer waste, highlighted with purple-colored bars.

In the higher separate collection scenario, there is a greater recovery of materials compared to the default system, resulting in an additional 2% reduction in climate change and energy use impact categories, and a 9% greater reduction in ecotoxicity, land use, and water use impact categories. Compared to the linear system, higher waste collection generates around 5% reduction in climate change and energy use impacts and approximately a 19% reduction in the other categories.

The scenario involving sorting and recycling in Norway shows similar impacts across all categories compared to the default scenario, with minor improvements in process contribution from electricity and transport. Electricity in the sorting and recycling process is based on the Norway electricity mix, which is greener than the Lithuanian and Chinese mixes used in default scenario. Transport benefits come from avoiding the need to send discarded t-shirts to Lithuania for sorting and then to China for recycling. However, after the recycling process, the recycled fibers still need to be sent to China for production into the next t-shirt, i.e., T-shirt 2.

The waste minimization scenario focuses on reducing waste throughout the production stages, from yarn production to apparel production. This impact reduction comes not only from the reduced demand for primary fiber due to the recovered fiber but also from processing a lesser amount of materials throughout the production chain, as the overall

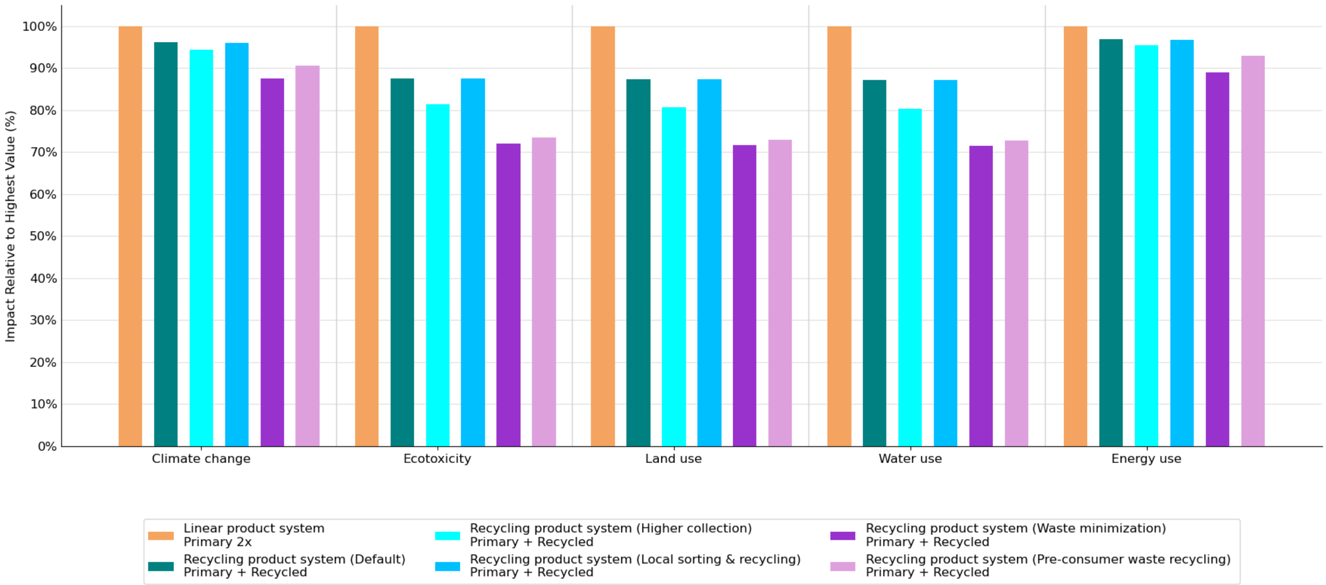


Figure 4.12: LCA results of linear and five recycling product system scenarios for cotton case, normalized to the highest impacts per impact category.

fibre demand to make a t-shirt is reduced by 16%. As a result, climate change and energy use impacts are reduced by 13%, while reductions in other impact categories are about 28% compared to the linear system. By minimizing waste at production stages, this scenario maximizes resource efficiency and environmental benefits.

The pre-consumer waste recycling scenario emphasizes the recycling of waste generated during the production processes. Hence, in this scenario, both pre-consumer and post-consumer waste are recycled simultaneously to recover the maximum amount of recycled fibres. By doing so, this scenario reduces the demand for primary fibre by the maximum amount and demonstrates notable environmental improvements of about 26% compared to linear system in ecotoxicity, land use, and water use impacts. For climate change and energy use, this scenario achieves reductions of 7 to 9%.

4.2.2 Polyester case

For the polyester case, the recycling product system does not show any noticeable benefit compared to the linear system. The combined production processes, including fibre, yarn, dyeing and apparel production, contribute significantly to the overall impact for climate change, ecotoxicity and energy use categories. For land use impact, the use phase contributes the highest share, while for water use impact, primary PET production, other production processes, distribution and use phase contribute almost equally to the total impact, as demonstrated in figure 4.13.

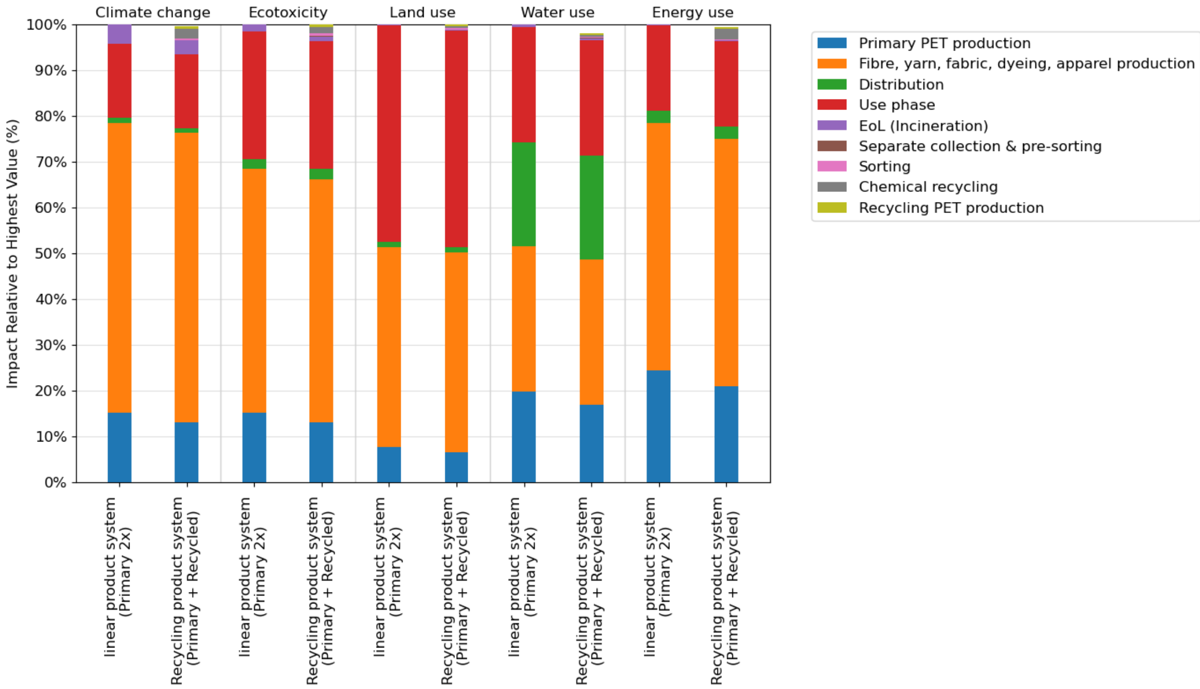


Figure 4.13: LCA results of both linear and recycling product system for polyester case, normalized to the highest impacts per impact category.

In the climate change category, the linear system causes an impact of 6.69 kg CO_2-eq., whereas the recycling system achieves only a 0.03 kg CO_2-eq reduction. Among the life cycle stages, virgin PET production, wet processing and use phase contribute significant share of 15%, 23% and 16%, respectively. Separate collection, sorting, chemical recycling, and regranulation processes together cause only 3% of the total impact.

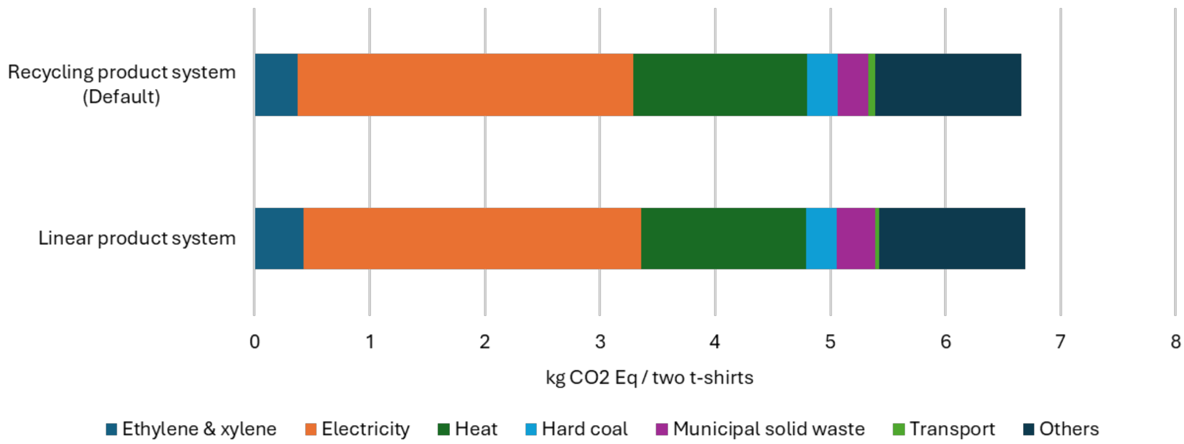


Figure 4.14: Contribution of background processes to climate change impact in polyester case.

Regarding background processes as shown in figure 4.14, climate change is dominated by electricity and heat used across many processes, with small share of impacts from ethylene and xylene during the primary PET production.

The impact results for ecotoxicity, land use, and water use are 2.47 CTUe, 0.16 m^2 and 0.06 m^3 in both product systems. It indicates that polyester t-shirts cause much less impact in these areas compared to cotton t-shirts. Interestingly, for ecotoxicity and land use impacts, the recycling product system causes slightly higher environmental impacts compared to the linear system. There are two reasons for this: virgin PET granulate production is responsible for only 8% of total impact, so the added impacts from the recycling product system for transport, collection, sorting, and recycling offset the benefits of 29% of recovered material added to the system, resulting in overall higher impact than linear system.

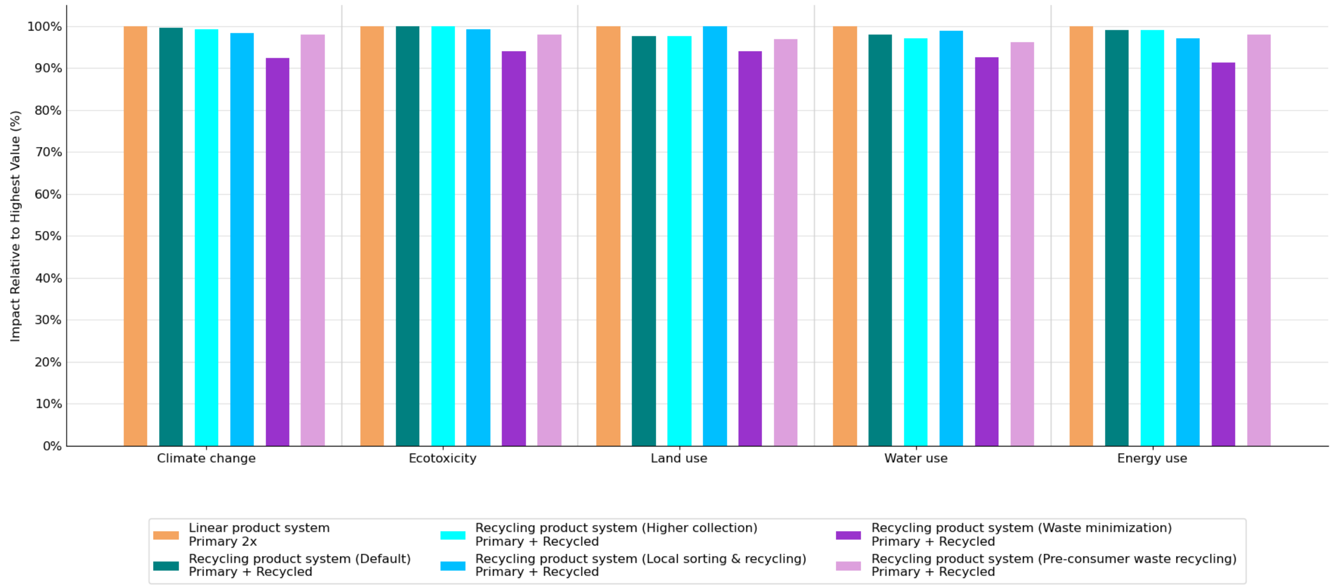


Figure 4.15: LCA results across linear and recycling product systems across five scenarios for polyester case, normalized to the highest impacts per impact category.

Scenario analysis

Similar to the comparison between the linear and recycling system for polyester, none of the scenarios show significant impact savings as shown in figure 4.15. This is due to the small share of primary PET production in the total impact for all categories. Therefore, the reduced demand for primary PET due to recovered recycled PET does not significantly impact the overall results. The only noticeable change is caused by the waste minimization scenario, as it requires the least amount of PET granulates to cover the material requirements for a t-shirt, making it comparatively less energy and resource-intensive. This scenario results in 8-9% lesser impact across all studied impact categories except for land use, where it causes a smaller reduction of 4.7%.

4.3 National level material flows and impact analysis

In 2018, the amount of new cotton and polyester t-shirts that entered the Norwegian clothing system was estimated at 3436 tonnes and 2398 tonnes, respectively. Cotton t-shirt consumption is 43% higher than polyester t-shirt consumption. As indicated in table 4.1, this volume is divided into two half-yearly groups: with 1718 tonnes for cotton and 1199 tonnes for polyester for each group.

Table 4.1: Norwegian household's consumption of t-shirts for 2018.

CN code	Description	Net import in 2018 (tons)	Groups	Amount (Tons)
610910	Cotton t-shirt	3436	Group 1 (Half yearly cons)	1718
			Group 2 (Half yearly cons)	1718
610990	Polyester t-shirt	2398	Group 1 (Half yearly cons)	1199
			Group 2 (Half yearly cons)	1199

The quantified MFA model for Norwegian yearly consumption of cotton and polyester t-shirt, assuming the system followed recycling product system, are shown in figure 7.6 and 7.7 in the appendix. In the recycling system, group 1 t-shirts will be recycled at the end of their lifecycle, and the recovered fibres will be reintroduced into the production of group 2 t-shirts.

For cotton t-shirts, the fibre required for group 1 was estimated to be 2758 tonnes, following the same production loss percentage as the default recycling scenario. Additionally, 17 tonnes of unsold t-shirts from stores were sent to incineration. After the use phase, 1021 tonnes of t-shirts would be collected for mechanical recycling, generating 757 tonnes of recycled fibres. Consequently, the demand for primary yarn for group 2 would be reduced to 2001 tonnes. Similarly, for polyester t-shirts, after the half-yearly consumption of polyester t-shirts, chemical recycling would yield 492 tonnes of recycled PET granulates.

From the LCIA results, it was estimated that if the Norwegian clothing system followed the recycling system, substantial amount of impact savings could be achieved for the year of 2018, as detailed in table 4.2 for cotton and table 4.3 for polyester. Since the recycling system shows higher impacts than the linear system for two studied impact categories for polyester t-shirts, this national-level impact calculation also shows negative values in the benefit column for polyester in table 4.3. However, because the recycling system for cotton brings higher benefit than the polyester recycling system, and national

Table 4.2: Potential environmental benefit from recycling product system for cotton t-shirts.

Impact categories	Unit	Linear product system	Recycling product system	Benefit
Climate change	kg CO_2-eq	1.10E+08	1.06E+08	4.07E+06
Ecotoxicity	CTUe	3.32E+08	2.91E+08	4.11E+07
Land use	m2*a crop-eq	3.44E+07	2.99E+07	4.42E+06
Water use	m3	2.27E+07	1.98E+07	2.95E+06
Energy use	MJ-eq	1.58E+09	1.53E+09	4.96E+07

consumption of cotton t-shirts is higher than that of polyester t-shirts, the overall impact benefits come positive. Based on the total t-shirt consumption, including cotton and polyester, the recycling product system could provide a 2%, equivalent to 4.44E+06 CO_2-eq and 5.64E+07 MJ-eq benefit for climate change and energy use and around a 12% benefit for other impact categories compared to the linear system as mentioned in table 4.4.

Table 4.3: Potential environmental benefit from recycling product system for polyester t-shirts.

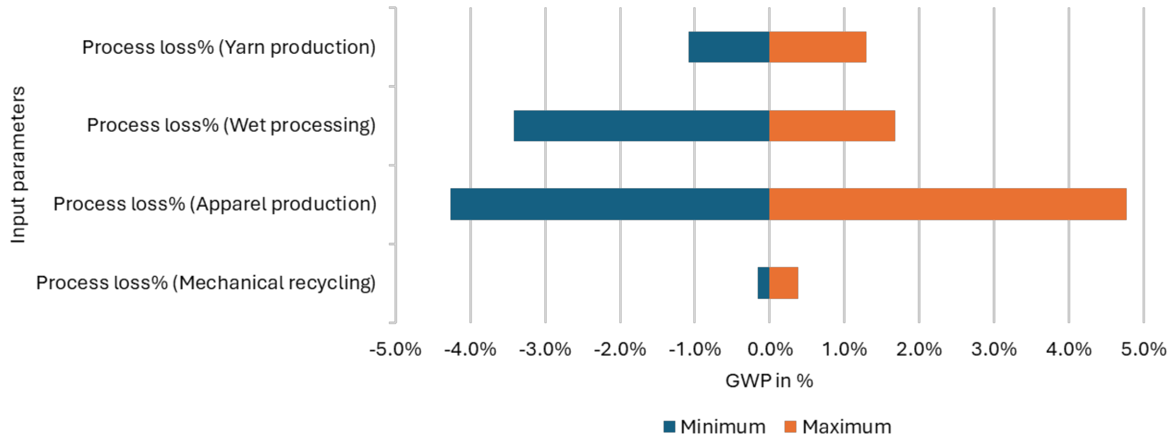
Impact categories	Unit	Linear product system	Recycling product system	Benefit
Climate change	kg CO_2-eq	7.22E+07	7.19E+07	3.63E+05
Ecotoxicity	CTUe	2.66E+07	2.66E+07	-1.36E+03
Land use	m2*a crop-eq	1.74E+06	1.74E+06	-2.33E+02
Water use	m3	6.11E+05	5.99E+05	1.19E+04
Energy use	MJ-eq	1.11E+09	1.10E+09	6.81E+06

Table 4.4: Overall potential environmental benefit from country-wide recycling product system across cotton and polyester t-shirts.

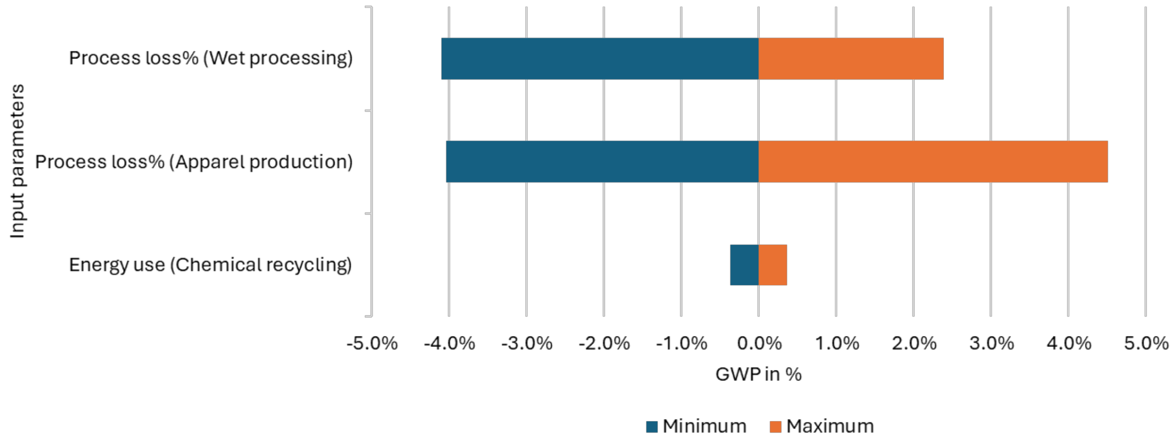
Impact categories	Unit	Net Benefit
Climate change	kg CO_2-eq	4.44E+06
Ecotoxicity	CTUe	4.11E+07
Land use	m2*a crop-eq	4.42E+06
Water use	m3	2.96E+06
Energy use	MJ-eq	5.64E+07

4.4 Uncertainty results

Figure 7.4 illustrates the changes in climate change impact relative to the default recycling product system when input parameters are varied within their uncertainty ranges. Variations in other impact categories are added in the appendix 7.3.



(a) Cotton product system.



(b) Polyester product system.

Figure 4.16: Sensitivity analysis of different parameters on climate change impact of default recycling production system in (a) cotton and (b) polyester cases.

The parameter of process loss percentage in apparel production exhibited the highest variation in climate change impact, ranging from -4.3% to +4.8% for cotton and -4.0% to +4.5% for polyester. When the process loss% is lowest, it results in less material input into the system, meaning reduced primary material production and less material processing in earlier production stages, thereby minimizing the impact compared to the default scenario with average process loss% consideration. Conversely, when the process loss is highest, it causes the maximum impact. Uncertainty related to process loss in mechanical recycling and energy input in chemical recycling showed minimal effect on the total impact, causing impact changes from -0.2% to +0.4% and -0.4% to +0.4% respectively.

5 Discussion

The purpose of this study is to understand the material flows of t-shirts across the supply chain and how recycling waste can improve the system performance. Furthermore, the study explores alternative scenarios that can increase the volume of recovered material, thus causing further environmental benefits. Four research questions were addressed in this study:

1. To what extent can the fibres in a t-shirt be recycled under a hypothetical recycling system, and how does this affect the demand for primary fibres in the recycled product compared to a t-shirt made entirely of virgin fibres?

2. What environmental benefits can be achieved if a t-shirt is recycled into a new one, rather than incinerated, comparing two different product systems, linear and recycling?

3. How might the environmental performance of these product systems be improved?

4. What is the environmental benefit if Norwegian clothing system can adopt a recycling product system?

MFA was used to answer the first question, indicating that around 27% to 29% of initial fibre material used in the production of a t-shirt can be recovered and reused. LCA addressed the second question, showing that only 3-13% benefit across different impact categories can be achieved for the cotton case, with no noticeable benefit for the polyester case. Combined MFA and LCA approaches were used in scenario analysis and for the Norwegian clothing system to answer the third and fourth questions, revealing that significant improvements in material recovery and environmental performance can be achieved by implementing certain parameter changes, such as higher collection of discarded garments, waste minimization during production stages and recycling pre-consumer waste.

5.1 Material flows across product systems

Interpretation of hypothetical product systems

This study developed two hypothetical product systems to demonstrate how consumers' choice regarding waste streams - residual waste versus separate collection - impacts the entire supply chain.

Linear product system:

- **Process:** Consumer purchases a t-shirt, uses it and then discards it into residual waste, repeating this cycle for the subsequent t-shirt.
- **Impact:** No recycling, leading to a continuous increase in waste and resource use.

Recycling product system:

- **Process:** After using the first t-shirt, consumer sends it to separate collection containers for recycling, and the recovered material is used in the production of a second t-shirt.
- **Impact:** Reduces waste and resource use by recycling materials.

To estimate material flows at different post-consumer operations such as separate collection or sorting, this study adopted material allocation from country-level and plant-level data. For example, in Norway, 60% of discarded clothing is collected by separate collectors after the use phase (Watson et al., 2020). This 60% share is applied to the product-level MFA in this thesis. The advantage of this approach is that the values from this MFA model can be easily scaled up to reflect material flows at country, regional, or global levels. However, this approach might cause some confusion. For instance, how can 60% of a t-shirt be separately collected while 40% of the same t-shirt ends up in residual waste? The answer is that the t-shirt is not physically torn apart. Instead, this study adopts region-wise waste collection percentage and applies them to the product-level MFA. To close the loop of the clothing system, two fibre-to-fibre recycling technologies were chosen as open-loop recycling options often create less value-added products and bring less environmental benefit compared to closed-loop recycling (Schmidt et al., 2016).

In practical cases, some good-quality garments are sorted for reuse during the sorting process. However, the recycling product system in this study assumes all such garments are recyclable to evaluate the maximum potential for material recovery in a clothing system adopting material recycling. Thus, the linear product system and the recycling product system represent two extreme scenarios: one with no recycling at all and the other with recycling as the sole circular economy approach. In reality, the percentage of recovered materials in any recycling clothing system adopted by any company or country would fall between these two extremes (0% to 29%, as found in this thesis) because other circular economy strategies such as reuse, resale, repair, renting, and cascade recycling would also be implemented.

Mapping of material loss

Material loss during manufacturing:

- **Cotton t-shirts:** 38% of the initial material is lost during manufacturing.
- **Polyester t-shirts:** 30% of the initial material is lost during manufacturing.

As there is no prior product-level MFA study for textile products, these numbers cannot be directly compared or validated with existing studies. However, if the material flows for t-shirts were upscaled to reflect global material flows for all clothing, it would indicate that at least 30% of materials are lost during the production stages. But the study by Ellen MacArthur Foundation (2017) reported only a 12% loss in production in their global clothing material flows model for 2015. This discrepancy arises because their assumptions on process loss during production stages are very low compared to other studies considered for this thesis (Alam et al., 2023, Moazzem, Crossin, et al., 2021, Sandin, Roos, et al., 2019). These studies utilized primary data from a large number of manufacturing factories to evaluate process loss at different production stages. For instance, Alam et al. (2023) collected primary data from 11 factories to determine process loss in apparel production, which was adopted in this thesis. It is also important to note that the 38% and 30% pre-consumer waste for cotton and polyester, respectively, are based on t-shirts, which are relatively simple garments that produce minimal waste. More complex garments generate more fabric waste, especially in cutting and sewing operations in apparel production process (Enes and Kipöz, 2020). Since global consumption includes a variety of garments, not just t-shirts, the loss of material during the production stages would be more than 30%, making the 12% process loss reported by Ellen MacArthur Foundation (2017) an underestimation of actual losses. Though the exact ratio of pre- and post-consumer waste across the supply chain estimated in this thesis and found in existing studies can be debated, it is generally agreed that the majority of waste is generated at the post-consumer level (McKinsey & Company, 2022, European Environment Agency, 2024). This thesis also estimates that, in both the linear and recycling product systems, more than 60% of total waste across the supply chain occurs when discarded t-shirts end up in mixed household waste.

Table 5.1: Material recovery across product systems.

Scenario	Recovered material (%) - Cotton case	Recovered material (%) - Polyester case
Default	27%	29%
Higher collection	41%	43%
Waste minimization	33%	33%
Pre-consumer waste recycling	57%	51%

Material recovery in clothing systems: Default and Alternative scenarios

In the recycling system, 49 grams of recycled cotton fibre, representing 27% of initial primary fibres and 46 grams of recycled PET granulates, representing 29% of initial primary PET volumes, are recovered. These recovery rates are based on specific process loss percentages at production phases, Norway's separate collection rate, and sorting and recycling efficiency at plants. Any fluctuation of any of these parameters affects the amount of recovered materials, as observed in the scenario analysis (Table 5.1).

The replacement rate was considered 1:1, assuming that recycled material can be used in the same way as primary raw materials. Scenario analysis showed that, except for the local sorting and recycling scenario in Norway, all other scenarios led to higher recovered materials, from 27% in the default scenario to 57% in the pre-consumer waste recycling scenario. Thus, recycling product systems have the potential to reduce the demand for primary raw materials by 27-57% across different scenarios.

The higher separate collection scenario aligns with the EU's WFD mandate for mandatory separate collection of textile waste from 2025 (European commission, 2023b). This scenario allows for 41% recovered material, 14% higher than the default scenario. The positive correlation between higher separate collection rates and higher recycling rates is supported by existing studies which consider higher collection rates a key circular economy strategy for the clothing industry (Dahlbo et al., 2017, McKinsey & Company, 2022). This scenario underscores the importance of robust collection systems, innovation in sorting and recycling processes, and profitable waste management models to handle the expected increased amount of collected waste (European Environment Agency, 2024).

In the waste minimization scenario, 33% of materials are estimated to be recycled, which is not significantly higher than the default recycling scenario. However, the significance lies in the 16% reduction in primary material demand for producing t-shirts. Implementing best material utilization practices across production units could achieve this reduction. Studies by Alam et al. (2023) and Moazzem, Crossin, et al. (2021) observed large variations in process loss percentages across surveyed factories. Common observed variations include marker efficiencies determining cutting wastages during apparel production and material efficiency in wet processing, mainly due to uneven dyeing and faulty fabric. This scenario demonstrates how material demand for primary materials changes with the parameter of process loss.

The scenario with maximum waste valorization is the pre-consumer waste recycling scenario. Here, both pre- and post-consumer waste were assumed to be recycled, resulting in 57% of total material used for t-shirt 1 being recycled in the cotton case, and 51% in the polyester case. This highlights how pre-consumer waste recycling impact the overall circularity of the system. Currently most pre-consumer waste is handled in a grey market lacking traceability regarding how dealers purchase, treat, and distribute these wastes and where the working conditions of the workers are often overlooked (Khairul Akter et al., 2022). Formal management of this waste through recycling can increase circularity, improve transparency of material flows, and reduce illegal activities related to the management of pre-consumer waste. This scenario is also promising because pre-consumer waste is relatively clean compared to post-consumer and industrial waste (Juanga-Labayen et al., 2022). Cleanliness leads to better recycling efficiency and higher quality recovered material than that made from post-consumer waste, as supported by the study by Arafat and Uddin (2022).

5.2 System performance

Interpretation of goal and scope in LCA

The functional unit of this LCA study is ‘use of two t-shirts’ which captures the life cycle impact over two consecutive lifecycles. This unconventional functional unit is designed to include the extended lifecycle of products recycled into new products, which conventional units (for example, ‘one kg of garment’, ‘per use of garments’, ‘one garment’, ‘per lifecycle of garment’) cannot capture. The system boundaries encompass the entire lifecycle of two t-shirts, allowing for the environmental burden of discarded waste from the previous lifecycle and the environmental benefit of recycled material to be accounted for in the production of new products. Although the locations of different processes do not mirror any specific supply chain, they are representative of a typical global supply chain in the clothing industry.

Analysis of LCIA results

While expectations were high, the results indicate that the recycling system for the cotton product offers only a 3-13% benefit across five impact categories. This benefit is primarily due to the reduced demand for primary cotton fibre as recycled fibre re-enters the production chain. Background process contribution analysis reveals that cotton seed accounts for only about 13% of the total impact for climate change and energy use, but contributes around 90% for ecotoxicity, land use and water use. Consequently, the inclusion of 27% recycled cotton fibre in the production of the second t-shirt yields more substantial benefits for ecotoxicity, land use and water use compared to climate change and energy use as observed in figure 4.6.

In addition to the impact of cotton seed, electricity and heat used across the supply chain are significant contributors to the environmental impact of both product systems. The importance of electricity in the textile supply chain was also highlighted by Sandin, Roos, et al. (2019), who showed that using solar power instead of the conventional electricity mix in the production stages could achieve a 36% climate change benefit over the lifecycle of a t-shirt. Fashion brands have also started recognizing the importance of utilizing clean electricity in their production supply chain. For example, H&M and Bestseller have agreed at COP28 to invest in a 500MW offshore wind power project in Bangladesh to support the availability of renewable energy in the manufacturing country and to reduce climate impact from their supply chain (Global Fashion Agenda, 2024). Despite extensive transportation modeled within the system boundaries, including the transport of goods between production processes, from the manufacturing country to the consumer country, and from consumer country to sorting and recycling facilities, interestingly, the background process of transportation contributes minimally to the overall impact. It accounts for less than 1% of climate change impacts and even less for other categories. Regarding foreground processes, wet processing is the most impactful for climate change and energy use categories, while primary cotton production is the most impactful for other categories.

Scenario analysis indicates that waste minimization and pre-consumer waste recycling scenarios offer the most environmental benefits, with a reduction of 7-29% across studied impact categories. The scenario involving sorting and recycling in Norway brought negligible benefit compared to the default scenarios. It was expected that reduced transport of goods and the use of Norway's greener electricity mix, compared to Lithuania and China, would result in significant benefits. However, the contribution of transportation to the overall impact is minimal, and the sorting and recycling are not highly electricity-intensive processes. Consequently, this scenario did not significantly improve the overall system performance.

For the polyester case, the environmental benefits brought by the recycling system are negligible, with no more than a 2% improvement in any impact category. In fact, recycling even causes slightly higher impacts for ecotoxicity and land use. This is because the impact of primary PET production is relatively small compared to other processes, so the inclusion of recycled PET granulates into further production does not significantly improve the system's performance. This finding is supported by Schmidt et al. (2016), who found that chemical recycling of discarded garments offsets the benefits of avoided emissions from recovering DMT and EG across many impact categories including climate change, acidification, and eutrophication. Similar to the cotton case, electricity and heat are significant impact-generating background processes, while wet processing is the most impactful foreground process for climate change and the use phase is the most impactful for the rest of the impact categories. Waste minimization and pre-consumer waste recycling are the best-performing scenarios for polyester, but still,the benefits do not exceed 9% across the impact categories.

There are no prior LCA studies encompassing the environmental impact of two lifecycles, making it difficult to compare the absolute values of the LCIA results with other studies. However, by dividing the total impact in half, a rough comparison with existing studies can be done. In this approach, the impact per lifecycle from this thesis can be calculated as 3.56 CO_2-eq for the linear system and 3.43 kg CO_2-eq for the recycling system. These values are slightly higher than those found by Sandin, Roos, et al. (2019) and Moazzem, Crossin, et al. (2021), who estimated around 3 kg CO_2-eq per lifecycle. This difference is primarily due to the higher process loss considerations in production stages in this thesis compared to those studies. Moreover, the process contributions to overall impacts in this study can be compared with other research studies since the number of lifecycles added to the system boundary does not significantly affect these contributions. The contribution of cotton production to the overall impact of the t-shirt in this study aligns with the findings of Moazzem, Crossin, et al. (2021) and Sandin, Roos, et al. (2019), which indicate that raw cotton fibre production contributes the highest share to land use (96%) and water depletion (73%) impacts. However, there are mismatches in process contributions to climate change across existing studies. For instance, while this study and Sandin, Roos, et al. (2019) found that production stages contribute the most to climate change, Moazzem, Crossin, et al. (2021) found that the use phase contributes the highest. Despite these variations, both Moazzem, Crossin, et al. (2021) and this study found that the background process of electricity usage across the supply chain is a significant contributor to climate change impact. For polyester t-shirts, the process contribution findings align with Horn et al. (2023), identifying the use phase and fabric production including wet processing as the most impactful processes.

5.3 Context of Norwegian t-shirt consumption

From table 4.1, it was observed that t-shirt consumption accounted for approximately 10% of the total clothing consumption, which was 61,000 tonnes in 2018. This figure contrasts with the finding of Mora-Sojo et al. (2023) who reported a 44% share. This discrepancy arises because their study included underwear, nightwear, socks, brassieres, handkerchiefs and some other garment types within the same category. Understanding the volume of t-shirts consumed by households and the expected number available for further treatment throughout the year can help optimize sorting and recycling processes. For instance, dedicating separate production lines for different garment types could enhance efficiency. T-shirts, being simpler garments without additional trims, are easier to sort and recycle compared to more complex garments with zippers or multi-fiber layers. Implementing garment collection by category through 'take-back' programs or any other options adopted in EPR schemes could further improve sorting and recycling efficiency.

The impact benefits outlined in table 4.4 suggest that if consumers choose to dispose their t-shirts in separate collection containers rather than residual waste, it could save approximately 0.84 kg CO_2-eq per capita, considering Norway's population of 5,295,619 (Statistics Norway, 2020). Given that the total environmental impact of Norwegian clothing estimated at 1.57 Mtonnes CO_2-eq (Mora-Sojo et al., 2023, this benefit represents 1/354 of the annual carbon footprint per capita for clothing items. It is important to note that t-shirt consumption represents only 10% of total consumption. A rough arithmetic exploration suggests that if the entire clothing system followed the recycling model, the benefits could amount to 1/35 of total footprint, which signifies substantial environmental savings. These savings could be further enhanced by applying alternative scenarios to the Norwegian yearly consumption of t-shirts.

5.4 Uncertainties and limitations

Key parameters and uncertainty analysis

Results from uncertainty analysis presented in section 4.4 indicate the overall reliability of the findings from the LCA analysis. This is because none of the parameters caused significant variations in the impact results relative to the default recycling product system. This outcome is because waste is generated across the entire supply chain, rather than concentrated in a single stage. Consequently, optimizing any specific production process alone would not yield a significant impact. Instead, collective improvements across all processes, as seen in the 'waste minimization scenario', where all processes had minimum process loss percentages, result in more substantial benefits. The uncertainties in key parameters primarily arise from variations in operational and technological efficiencies across manufacturing units and treatment plants. These variations might include differences in the use of advanced machinery, the skill level of workers, and the effectiveness of material management practices.

Assumptions on production parameters in the second lifecycle

It was assumed in this study that in the recycling system, the production parameters- such as process loss, required energy and materials- of the second t-shirt remain the same as those of the first t-shirt. Although there is no evidence suggesting that the production process of garments containing recycled materials differs from those containing primary materials. However, one study suggests that their studied recycled cotton fibre does not require dyeing in its next lifecycle (Esteve-Turrillas and De La Guardia, 2017). Their suggestion is based on the use of 'Recover' cotton, produced through a novel procedure that involves segregating discarded garments by color during the sorting process, followed by cutting, shredding and color mixing to create recycled fibre that is already colored. This fibre is then mixed with primary fibres to achieve the required yarn strength. However, it is unclear from the paper and the 'Recover' website (Recover Textile, 2024) whether the primary fibres are dyed. If primary fibres are dyed in fibre form, the claim of 'no dyeing required' is not entirely accurate. If primary fibres are not dyed, it raises questions about the color consistency of fabric made from 'Recover' yarn containing both colored recycled fibre and non-colored primary fibre. Due to these uncertainties, this technology was not included in this thesis. However, incorporating such technology into the value chain could significantly improve the environmental performance of recycling system since wet processing is one of the highest impact-generating processes across all impact categories.

Replacement rate and technological limit

A 1:1 replacement rate is realistic for polyester, where chemical recycling converts discarded textiles into monomers, which are then polymerized into granulates of similar quality to primary PET (Sandin and Peters, 2018). However, for cotton, mechanical recycling results in shorter fibre lengths due to the cutting and shredding, reducing the quality of recycled fibres compared to primary cotton fibres (Schmidt et al., 2016). To achieve the required quality, recycled fibres must be mixed with primary fibres during the spinning process to produce recycled yarn. Yarn containing 30% recycled fibre can successfully be utilized in the production of knit garments, ensuring necessary strength and durability (Arafat and Uddin, 2022). This technical limitation for recycled cotton fibres was not included in the MFA models for cotton. While the default scenario's 27% recycled fibres fall within the technical limit, scenarios with higher collection and pre-consumer waste recycling, where 41 to 57% of material can be retrieved from t-shirt 1, assumed that the extra 11 to 27% (from the 30% technical limit) of material could be reutilized in the yarn production of t-shirt 2 for simplification purposes. Similarly, the LCIA also includes the benefits of all recovered fibres. This interpretation assumes that if technological improvements in yarn spinning allowing more short fibres from the recycling process to be included without compromising quality or if advancements in the recycling process can maintain fibre length within an optimal range, then any ratio of recycled fibres can be mixed with virgin fibres to produce yarn. This would result in material flows and environmental benefits as found in the study. However, if these technological improvements are not achieved, the recycling system may generate a large amount of recycled cotton that cannot be recirculated into the system. In other words, closed-loop recycling would not be achieved and the retrieved material would need to be downcycled for less value-added products or used in other garments besides t-shirts where recovered material percentage from their own recycling system is lower than that of t-shirts'.

Assumption on mass balance of the system

In the study, it was assumed that the material inflows and outflows of all processes are mass balanced without considering stock changes. For production processes, this assumption aligns with the reality that there is unlikely to be any accumulation of materials in any processes involved. However, during the use phase, there are indications that household stock of clothing is likely to increase in many developed countries (Dahlbo et al., 2017, Mora-Sojo et al., 2023, Watson et al., 2020). Since this stock change is not accounted for in this thesis, it may lead to an overestimation of material ending up in residual waste.

5.5 Future work and recommendation

Developing complex model

There has been a lack of studies addressing material flows and environmental performance of closed-loop recycling product system where recycled materials can be added to the production of the same products. This study attempted to fill this gap by using MFA and LCA to calculate the potential amount of recycled material in the system and the associated environmental benefits. Therefore, there are opportunities to develop more complex models including other feasible circular economy strategies such as reuse, resell, repair, and open-loop recycling. These models could compare the performance across different strategies and offer more holistic solutions to the problems imposed by current clothing systems. This approach is based on the understanding that no single solution or strategy can address all the associated problems in the clothing industry due to its complexity (Ellen MacArthur Foundation, 2017). For instance, although focusing on only one lifecycle, Horn et al. (2023) implemented a complex model and evaluated the environmental impact of a polyester t-shirt's full value chain over seven different scenarios, including incineration, reuse, renting, recycling, and combinations of a few strategies.

Garment lifetime and dynamic MFA

The effect of garment lifetime should be studied in detail to incorporate the increase in wardrobe or stock change during the use phase and to estimate more accurately the volume of materials in residual waste and other waste flows. Dynamic MFA modelling for textile products can be particularly useful in this regard, and currently, no study has modelled textile flows using dynamic MFA.

Primary source data for environmental assessment

Finding primary sources of life cycle inventory data is quite challenging for an environmental assessment, especially for the end-of-life operations. Most current studies that include recycling used either secondary data or data not disclosed due to confidentiality (Sandin and Peters, 2018). Efforts should be made in future to develop the latest life cycle inventory for both well-established recycling technologies and those not yet fully matured for commercialization, such as chemical recycling, and thermo-chemical recycling. Moreover, technological advancements and their inventory need to be in place for automatic sorting aimed at handling large amounts of discarded clothing effectively and efficiently. The purpose of automatic sorting is not only to phase out current manual sorting, which is labor-intensive and expensive, but also to sort garments accurately based on their color, composition, reusability, and recyclability.

Policy-related research

Through the scenario analysis, this study shows the possibility of improving the environmental performance of the system. However, it does not detail how these scenarios can be implemented in practice and their policy implications. Therefore, there are opportunities for future research to study policies related to textile waste management. For instance, this thesis has shown that separate collection could add significant benefits to the system, but it remains crucial to determine the policies needed to accelerate separate collection and formulate extended producer responsibility (EPR) more effectively. Such policies should consider the cost of downstream waste management operations and the eco-design of products to ensure they can be reused, recycled, or repaired at the end of their life. To understand how such EPR schemes work and evaluate their performance, thorough analysis of the clothing systems in countries like France and the Netherlands, which have already introduced EPR Scheme, is essential (Miljøstyrelsen, 2020, Ministry of Infrastructure and Water management, The Netherlands, 2023).

Exploration of extended lifecyles

In this thesis, an attempt was made to determine the material flows and environmental impacts if the lifespan of material extends to a second life. Since recycled PET offers similar quality to virgin materials, it would be interesting to develop MFA and LCA models for continuous lifecyle loops, rather than just two lifecycles as studied in this thesis. This would provide insights into the long-term benefits and challenges of sustained recycling practices.

Other recommendation

Consumers should prioritize sustainable consumption over the appealing advertisements from fast fashion brands that aim to attract more consumers. Raising awareness and educating consumers about the environmental footprint of their consumption and the benefits of textile recycling can drive behavior change away from over-consumption and support recycling initiatives.

Governments and industry stakeholders should collaborate to create policies that prevent illegal practices related to waste management and invest in advanced recycling technologies and infrastructure to handle the increasing volume of textile waste, especially in manufacturing countries. While global business leaders are increasingly addressing post-consumer wastes, concerns related to pre-consumer waste are often overlooked and need more attention.

Subsidies or financial contribution based on the volume of clothes found in residual waste should be part of an EPR scheme to boost eco-design and the collection of used clothes sold by brands. For instance, brands whose garments are found more frequently in residual waste should financially contribute more to the EPR scheme. Additionally, restrictions on mixed fibre composition should be implemented in the design stage of clothing, except where mixed compositions are absolutely required for functionality.

Automatic and effective sorting should be given extra attention. Separately collected garments by charitable organizations from Europe and North America are given away to those in need or sold in the global market to raise money. However, many traders who buy second-hand garments from large-scale sorters or charitable organizations, purchase bales of used clothing without knowing the quality of garments inside the bale. This often results in a significant number of garments ending up in landfills because their quality is too poor to be sold to consumers seeking decent second-hand clothes. This is particularly prevalent in third-world countries where second-hand clothes often end up as donations or as part of a business model, and where there is a lack of technology to recycle the unsold garments(Marc and CNN, 2023). Another report by The Independent (2022) highlighted that in Ghana, 40% of the second hand clothes received by traders never find a buyer, and ultimately end up in the ocean or in landfills. Proper sorting would minimize this effect, ensuring second-hand market traders can purchase the appropriate quality garments, reducing the risk of buying bales of unsellable clothing, and selling unsellable clothing to recyclers immediately after sorting to recover materials.

Similar to the EU's End-of-Life vehicles (ELV) directive for the automobile industry (Giampieri et al., 2020), a directive could be implemented in the clothing industry. This directive would set a maximum limit on waste generated during manufacturing processes or require garment manufacturers to achieve a certain percentage of material recovery from that waste. Currently, there is no mandatory requirement for garment factories to separately collect or recycle their fabric or apparel cutting waste. In a study by Maria (2021), the author mentioned the laws for garment factories located in Moldova, but the situation is similar across the globe. Implementing such policies at the level of clothing brands or manufacturing industries could significantly enhance material recovery and reduce waste in the clothing sector.

6 Conclusion

This research aimed to map material flows of cotton and polyester t-shirts across the global supply chain, exploring the potential for recovering discarded waste through recycling and the associated environmental benefits. Through material flow analysis (MFA), it was concluded that waste is generated across the entire supply chain, with pre-consumer waste accounting for 30-38% of total waste and post-consumer waste comprising the rest for both cotton and polyester t-shirts. Implementing a recycling product system in the Norwegian clothing system, where t-shirts are separately collected for recycling instead of being discarded as residual waste, could recover approximately 27-29% of primary raw material. Life cycle assessment (LCA) results indicate that this recovered material reduces the demand for primary materials for subsequent t-shirt production, resulting in a 3-13% environmental benefit across different impact categories for cotton. However, for polyester, the benefits are negligible.

The varying percentage of environmental benefits across impact categories and between cotton and polyester stems from the fact that the system's benefits are derived from the avoided production of primary raw materials due to recovered cotton fibres or polyethylene terephthalate (PET) granulates and the production of these primary raw materials does not contribute equally across all impact categories. For instance, cotton cultivation significantly impacts land use and water use, resulting in around a 13% benefit in these impact categories, but contributes less to climate change, resulting in only a 4% benefit. Similarly, PET production has a minimal contribution to all impact categories, leading to minimal benefits from recovered PET granulates.

Scenario analysis results indicate that optimizing key system parameters, such as increasing the collection rate, minimizing waste in production stages, and recycling pre-consumer waste, can significantly improve the outcomes of the recycling system. This optimization could result in a maximum of 57% recovered material, leading to a 4-29% environmental benefit for cotton, though the benefit for polyester remains minimal. This study highlights the importance of process optimization and treatment of waste generated at production stages, an area currently less discussed among stakeholders in the global fashion industry compared to post-consumer waste. This oversight means that a significant amount of material waste in garment production is not adequately highlighted. One reason for this could be the underestimation of pre-consumer waste in many business reports and research papers compared to real numbers.

This thesis developed a new framework for LCA that includes two lifecycles of two t-shirts to capture the recovered material from one lifecycle and reintroduce it into the next t-shirt production, accounting for the environmental burden of the waste material. Existing frameworks of current studies cannot capture the material flows and benefit of this recovered material transitioning from one lifecycle to another and often consider waste as a burden-free material in the recycling process.

This thesis assumed the same production stages and production recipe for the second lifecycle as for the first. However, incorporating promising technologies, such as 'no dyeing required' for recycled fibre in the second lifecycle, would significantly increase environmental savings, as wet processing is one of the highest contributing processes across all impact categories. Future research should include such recycling technologies including the inclusion of higher or any ratio of recycled fibre while maintaining yarn quality, and other circular economy strategies, such as reuse, resell, renting, and open-loop recycling in research models to explore the full potential of clothing system circularity. Detailed research into policies that can facilitate the implementation of these strategies is also essential.

Recycling of garment waste not only reduces the demand for primary raw materials but also decreases the amount of waste, currently the majority of which ends up in landfills. This comprehensive study provides a better understanding of material flows at the product level, from raw material to end-of-life treatments, and the associated environmental impacts at every stage. By understanding the impact of different scenarios by changing key system parameters on material flows and environmental benefits, these results could serve as a foundation for further exploration of how the clothing system can move towards greater circularity.

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7 Appendix

7.1 Life cycle inventory modelling

This section begins with the modelling of the fictional electricity mix used in the production stages. The section is then divided into two subsections 7.1.1 and 7.1.2 for presenting unit processes modelling for the cotton and polyester case respectively.

Table 7.1: Modelling of fictional electricity mix.

Outputs	**Quantity**	**Unit**	**Dataset**	**Reference**
Electricity mix for textile production	1	kWh		
Input	**Quantity**	**Unit**	**Dataset**	**Reference**
Electricity mix from China	0.55	kWh	market group for electricity, medium voltage, CN, ecoinvent38 APOS	
Electricity mix from Bangladesh	0.12	kWh	market for electricity, medium voltage, BD, ecoinvent38 APOS	
Electricity mix from Turkey	0.09	kWh	market for electricity, medium voltage, TR, ecoinvent38 APOS	
Electricity mix from India	0.08	kWh	market group for electricity, medium voltage, IN, ecoinvent38 APOS	
Electricity mix from Germany	0.06	kWh	market for electricity, medium voltage, DE, ecoinvent38 APOS	
Electricity mix from Vietnam	0.05	kWh	market for electricity, medium voltage, VN, ecoinvent38 APOS	
Electricity mix from Italy	0.05	kWh	market for electricity, medium voltage, IT, ecoinvent38 APOS	

7.1.1 cotton case

Table 7.2: Modelling of fibre production.

Outputs	**Quantity**	**Unit**	**Dataset**	**Reference**
Fibre	1	kg	fibre production, cotton, ginning, RoW, ecoinvent38 APOS	

Table 7.3: Modelling of yarn production.

Outputs	**Quantity**	**Unit**	**Dataset**	**Reference**
Yarn	1	kg		
Waste to incineration	0.19	kg	treatment of municipal solid waste, incineration, RoW, ecoinvent38	Moazzem, Crossin, et al. (2021)
Input	**Quantity**	**Unit**	**Dataset**	**Reference**
Fibre	1.19	kg		Moazzem, Crossin, et al. (2021)
Lubricant (A)	0.0016	kg	As (A) Lubricant	Sandin, Roos, et al. (2019)
Electricity	4.0	kWh	Fictional electricity mix	Sandin, Roos, et al. (2019)

Table 7.4: Modelling of (A) Lubricant.

Outputs	Quantity	Unit	Dataset	Reference
Lubcricant	1	kg		
Input	**Quantity**	**Unit**	**Dataset**	**Reference**
Acrylic acid	0.1	kg	market for acrylic acid, RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Polyacrylamide	0.2	kg	market for polyacrylamide, GLO, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Water, ultrapure	0.7	kg	market for water, ultrapure, RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)

Table 7.5: Modelling of fabric production.

Outputs	Quantity	Unit	Dataset	Reference
Fabric	1	kg		
Waste to incineration	0.02	kg	treatment of municipal solid waste, incineration, RoW, ecoinvent38 APOS	Alam et al. (2023)
Inputs	**Quantity**	**Unit**	**Dataset**	**Reference**
Yarn	1.02	kg		Alam et al. (2023)
Electricity	0.5	kg	Fictional electricity mix for production	Alam et al. (2023)
Lubricant, average	0.08	kg	As (A) Lubricant	Sandin, Roos, et al. (2019)
Transport of goods (By truck)	0.255	tkm	market for transport, freight, lorry, unspecified, RoW, ecoinvent38 APOS	Dinkel et al. (2007)

Table 7.6: Modelling of (B) Detergent, average.

Outputs	Quantity	Unit	Dataset	Reference
Detergent, average	1	kg		
Input	**Quantity**	**Unit**	**Dataset**	**Reference**
Acrylic acid	0.1	kg	market for acrylic acid, RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Dimethyl sulfate	0.05	kg	market for dimethyl sulfate, RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Ehoxylated alcohol (AE3)	0.25	kg	market for ethoxylated alcohol (AE3), RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Ehoxylated alcohol (AE7)	0.1	kg	market for ethoxylated alcohol (AE7), RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Water, ultrapure	0.5	kg	market for water, ultrapure, RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)

Table 7.7: Modelling of (C) Peroxide stabilizer.

Outputs	Quantity	Unit	Dataset	Reference
Peroxide stabilizer, average	1	kg		
Input	**Quantity**	**Unit**	**Dataset**	**Reference**
Acrylic acid	0.1	kg	market for acrylic acid, RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Magnesium oxide	0.005	kg	market for magnesium oxide, GLO, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Phosphoric acid	0.1	kg	market for phosphoric acid, industrial grade, without water, in 85% solution state, GLO, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Water, ultrapure	0.795	kg	market for water, ultrapure, RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)

Table 7.8: Modelling of (D) Softener.

Outputs	Quantity	Unit	Dataset	Reference
Softener, average	1	kg		
Input	**Quantity**	**Unit**	**Dataset**	**Reference**
Diethanolamine	0.03	kg	market for diethanolamine, GLO, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Stearic acid	0.2	kg	market for stearic acid, GLO, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Water, ultrapure	0.77	kg	market for water, ultrapure, RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)

Table 7.9: Modelling of wet processing.

Outputs	Quantity	Unit	Dataset	Reference
Finished fabric	1	kg		
Waste to incineration	0.12	kg	MSW incineration, RoW, ecoinvent38 APOS	Alam et al. (2023)
COD, Chemical Oxygen Demand	0.0002	kg	COD, biosphere3	Sandin, Roos, et al. (2019)
Water to treatment	0.045	m3	market for wastewater from textile production, GLO, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Input	**Quantity**	**Unit**	**Dataset**	**Reference**
Fabric	1.12	kg		Alam et al. (2023)
Water	60	kg	tap water production, RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Detergent/wetting agent, average	0.05	kg	acrylic acid, RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Fluorescent whitening	0.06	kg	fluorescent whitening agent, GLO, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Formic acid	0.01	kg	formic acid, RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)

Table 7.10: Modelling of wet processing (Continue).

Inputs	Quantity	Unit	Dataset	Reference
Hydrogen peroxide	0.07	kg	hydrogen peroxide, RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Lubricant, average	0.08	kg	As A. Lubricant	Sandin, Roos, et al. (2019)
Peroxide stablizer (C)	0.002	kg	As C. Peroxide stablizer	Sandin, Roos, et al. (2019)
Sodium hydroxide	0.025	kg	sodium hydroxide, GLO, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Softener (D)	0.03	kg	As D.Softener	Sandin, Roos, et al. (2019)
Sulphuric acid	0.02	kg	sulfuric acid, RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Electricity (Combined for dyeing and finishig)	1.5	kWh	Fictional electricity mix	Sandin, Roos, et al. (2019)
Heat (Combined for dyeing and finishing)	38	MJ	heat production, light fuel oil, RoW ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Transport of goods (By truck)	0.28	tkm	transport, freight, lorry, unspecified, RoW, ecoinvent38 APOS	Dinkel et al. (2007)

Table 7.11: Modelling of Apparel production.

Outputs	Quantity	Unit	Dataset	Reference
Garment	1	kg		
Waste to incineration	0.18	kg	treatment of municipal solid waste, incineration, RoW, ecoinvent38 APOS	Alam et al. (2023)
Input	**Quantity**	**Unit**	**Dataset**	**Reference**
Finished fabric	1.18	kg		Alam et al. (2023)
Water	0.18	kg	market group for tap water, GLO, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Sewing thread	0.0035	kg	market for fibre, polyester, GLO, ecoinvent 38 APOS	Sandin, Roos, et al. (2019)
Confectioning template	0.05	kg	market for kraft paper, RoW, ecoinvent 38 APOS	Sandin, Roos, et al. (2019)
Packaging film	0.02	kg	market for packaging film, low density polyethylene, GLO, ecoinvent 38 APOS	Sandin, Roos, et al. (2019)
Corrugated board box	0.06	kg	market for corrugated board box, RoW, ecoinvent 38 APOS	Sandin, Roos, et al. (2019)
Electricity (Including ironing)	2.711	kWh	Fictional electricity mix	Sandin, Roos, et al. (2019)
Heat	3.6	MJ	heat production, natural gas, at boiler modulating 100kW, RoW, ecoinvent 38 APOS	Roos et al. (2015)
Transport of goods (By truck)	0.295	tkm	market for transport, freight, lorry, unspecified, RoW, ecoinvent 38 APOS	Dinkel et al. (2007)

Table 7.12: Modelling of distribution.

Outputs	Quantity	Unit	Dataset	Reference
Distributed garment	1	kg		
Waste to incineration	0.01	kg	treatment of municipal solid waste, incineration, NO, ecoinvent38	Sandin, Roos, et al. (2019)
Input	**Quantity**	**Unit**	**Dataset**	**Reference**
Garment	1.01	kg		Sandin, Roos, et al. (2019)
Transport of goods (By truck)	0.253	tkm	market for transport, freight, lorry, unspecified, RoW, ecoinvent38	Dinkel et al. (2007)
Transport of goods (Sea)	20.63	tkm	market for transport, freight, sea, container ship, GLO, ecoinvent38	Sea-Distances.org (n.d.)
Transport of goods (By truck)	0.08	tkm	market for transport, freight, lorry 16-32 metric ton, EURO6, RER, ecoinvent 38 APOS	Assumption
Transport of goods (By truck)	0.03	tkm	market for transport, freight, lorry 16-32 metric ton, EURO6, RER, ecoinvent 38 APOS	Assumption
Electricity for Facility management (Warehouse)	0.00927	kwh	market for electricity, low voltage, NO, ecoinvent 38 APOS	Mora-Sojo et al. (2023)
Electricity Facility management (Store)	1.94	kwh	market for electricity, low voltage, NO, ecoinvent 38 APOS	Sandin, Roos, et al. (2019)

Table 7.13: Modelling of use phase.

Outputs	Quantity	Unit	Dataset	Reference
Used garment	1	kg		
Input	**Quantity**	**Unit**	**Dataset**	**Reference**
Distributed garment	1	kg		
Washing, drying and finishing	15	kg	market for washing, drying and finishing laundry, GLO, ecoinvent38 APOS	Sandin, Roos, et al. (2019)

Table 7.14: Modelling of incineration.

Outputs	Quantity	Unit	Dataset	Reference
Incinerated garment	1	kg	treatment of municipal solid waste, incineration, NO, ecoinvent38 APOS	
Input	**Quantity**	**Unit**	**Dataset**	**Reference**
Used garment	1	kg		
Transport of goods (By truck)	0.014	tkm	market for municipal waste collection service by 21 metric ton lorry, GLO, ecoinvent38 APOS	Mora-Sojo et al. (2023)
Transport of goods (By truck)	0.05	tkm	market for transport, freight, lorry 3.5-7.5 metric ton, EURO6, RER, ecoinvent38 APOS	Mora-Sojo et al. (2023)

Table 7.15: Modelling of separate collection and pre-sorting

Outputs	Quantity	Unit	Dataset	Reference
Pre-sorted garment	1	kg		
Waste to incineration	0.012	kg	treatment of municipal solid waste, incineration, NO, ecoinvent 38 APOS	Mora-Sojo et al. (2023)
Input	**Quantity**	**Unit**	**Dataset**	**Reference**
Collected garment	1.012	kg		Mora-Sojo et al. (2023)
Transport of goods (By truck)	0.15	tkm	market for transport, freight, lorry 7.5-16 metric ton, EURO6, RER, ecoinvent 38 APOS	Mora-Sojo et al. (2023)
Electricity	0.07	kWh	market for electricity, low voltage, NO, ecoinvent 38 APOS	Schmidt et al. (2016)

Table 7.16: Modelling of sorting at European sorting center.

Outputs	Quantity	Unit	Dataset	Reference
Sorted garment	1	kg		
Waste to incineration	0.07	kg	treatment of municipal solid waste, incineration, RoW, ecoinvent 38 APOS	Nørup et al. (2019)
Input	**Quantity**	**Unit**	**Dataset**	**Reference**
Pre-sorted garment	1.07	kg		Nørup et al. (2019)
Electricity	0.0161	kwh	market for electricity, low voltage, LT, ecoinvent 38 APOS	Nørup et al. (2019)
Gas for heating	0.0259	MJ	heat and power co-generation, natural gas, conventional power plant, 100MW electrical, LT, ecoinvent 38 APOS	Nørup et al. (2019)
Bailing wire	0.0007	kg	wire drawing, steel, RER, ecoinvent 38 APOS	Nørup et al. (2019)
Water	0.0001	l	Tap water, RER, ecoinvent 38 APOS	Nørup et al. (2019)
Transport of goods (By truck)	0.57	tkm	market for transport, freight, lorry 7.5-16 metric ton, EURO6, RER, ecoinvent 38 APOS	Google Maps (n.d.)
Transport of goods (Ferry)	0.29	tkm	market for transport, freight, sea, ferry, GLO, ecoinvent 38 APOS	Google Maps (n.d.)
Transport of goods (By truck)	0.47	tkm	market for transport, freight, lorry 7.5-16 metric ton, EURO6, RER, ecoinvent 38 APOS	Google Maps (n.d.)

Table 7.17: Modelling of mechanical recycling.

Outputs	Quantity	Unit	Dataset	Reference
Recycled cotton fibre	0.8	kg		
Waste to incineration	0.2	kg	treatment of municipal solid waste, incineration, RoW, ecoinvent 38 APOS	Schmidt et al. (2016)
Input	**Quantity**	**Unit**	**Dataset**	**Reference**
Sorted garment	1	kg		Schmidt et al. (2016)
Electricity	0.10	kWh	market group for electricity, medium voltage, CN, ecoinvent 38 APOS	Schmidt et al. (2016)
Transport of goods (By truck)	0.31	tkm	market for transport, freight, lorry 7.5-16 metric ton, EURO6, RER, ecoinvent 38 APOS	Google Maps (n.d.)
Transport of goods (Sea)	21.1	tkm	market for transport, freight, sea, container ship, GLO, ecoinvent 38 APOS	Sea-Distances.org (n.d.)
Transport of goods (By track)	0.25	tkm	market for transport, freight, lorry, unspecified, RoW, ecoinvent 38 APOS	Dinkel et al. (2007)

7.1.2 Polyester case

Table 7.18: Modelling of polyester fibre production.

Outputs	Quantity	Unit	Dataset	Reference
Polyester fibre	1.000	kg		
Waste paperboard	0.018	kg	treatment of waste paperboard, inert material landfill, RoW, ecoinvent38 APOS	Ecoinvent
Waste plastic	0.015	kg	market for waste plastic, mixture, RoW, ecoinvent38 APOS	Ecoinvent
Hazarous waste	0.005	kg	market for hazardous waste, for underground deposit, RoW, ecoinvent38 APOS	Ecoinvent
Waste water	0.023	kg	market for wastewater, average, RER, ecoinvent38 APOS	Ecoinvent
Waste mineral oil	0.016	kg	market for waste mineral oil, RER, ecoinvent38 APOS	Ecoinvent
Inputs	**Quantity**	**Unit**	**Dataset**	**Reference**
PET granulate	1.014	kg		Ecoinvent
Tap water	22.754	kg	market for tap water, RoW, ecoinvent38 APOS	Ecoinvent
Heat	2.019	MJ	heat production, natural gas, at industrial furnace 100kW, RoW, ecoinvent38 APOS	Ecoinvent
Electricity	1.102	kWh	Fictional electricity mix	Ecoinvent
Lubricating oil	0.016	kg	market for lubricating oil, RoW, ecoinvent38 APOS	Ecoinvent

Table 7.19: Modelling of yarn production.

Outputs	Quantity	Unit	Dataset	Reference
Polyester yarn	1	kg		
waste to incineration	0.04	kg	treatment of municipal solid waste, incineration, RoW, ecoinvent38 APOS	Moazzem, Crossin, et al. (2021)
Inputs	**Quantity**	**Unit**	**Dataset**	**Reference**
Polyester fibre	1.04	kg		Moazzem, Crossin, et al. (2021)
Lubricant, average	0.0016	kg	As (A) Lubricant, average	Sandin, Roos, et al. (2019)
Electricity	3.8	kwh	Fictional electricity mix for production	Sandin, Roos, et al. (2019)
Transport of goods (By truck)	0.260	tkm	market for transport, freight, lorry, unspecified, RoW, ecoinvent38	Dinkel et al. (2007)

Table 7.20: Modelling of fabric production.

Same as cotton fabric production

Table 7.21: Modelling of E.Reducing agent VAT, avg

Outputs	Quantity	Unit	Dataset	Reference
Reducing agent VAT, avg	1	kg		
Inputs	**Quantity**	**Unit**	**Dataset**	**Reference**
calcium carbonate, precipitated	0.02	kg	market for calcium carbonate, precipitated, RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
sodium dithionite, anhydrous	0.9	kg	market for sodium dithionite, anhydrous, RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
sodium sulfite	0.08	kg	market for sodium sulfite, RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)

Table 7.22: Modelling of F. Wetting/penetrating agent

Outputs	Quantity	Unit	Dataset	Reference
Wetting / penetrating agent, synthetic	1	kg		
Inputs	**Quantity**	**Unit**	**Dataset**	**Reference**
fatty alcohol	0.1	kg	market for fatty alcohol, GLO, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
maleic anhydride	0.2	kg	market for maleic anhydride, GLO, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
water, ultrapure	0.7	kg	market for water, ultrapure, RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)

Table 7.23: Modelling of wet processing.

Outputs	Quantity	Unit	Dataset	Reference
Finished fabric	1	kg		
Waste to incineration	0.12	kg	MSW incineration, RoW, ecoinvent38 APOS	Alam et al. (2023)
COD, Chemical Oxygen Demand	0.0002	kg	COD, biosphere3	Sandin, Roos, et al. (2019)
Water to treatment	0.045	m3	market for wastewater from textile production, GLO, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Input	**Quantity**	**Unit**	**Dataset**	**Reference**
Polyester fabric	1.12	kg		Alam et al. (2023)
Water	78	kg	tap water production, RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Ammonium sulphate	0.01	kg	market for ammonium sulfate, RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Aniline	0.05	kg	market for aniline, RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)

Table 7.24: Modelling of wet processing (continue).

Inputs	Quantity	Unit	Dataset	Reference
Detergent, average	0.075	kg	As B.Detergent, average	Sandin, Roos, et al. (2019)
Detergent/wetting agent average	0.02	kg	market for acrylic acid, RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Ethylene glycol	0.015	kg	market for ethylene glycol, RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Formic acid	0.015	kg	market for formic acid, RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Hydrogen peroxide	0.015	kg	market for hydrogen peroxide, RoW, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Reducing agent VAT, avg	0.005	kg	See E.Reducing agent VAT, avg	Sandin, Roos, et al. (2019)
Sequestering agent	0.02	kg	market for phosphoric acid, GLO, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Soda ash	0.0225	kg	market for soda ash, dense, GLO, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Sodium hydroxide	0.005	kg	market for sodium hydroxide, GLO, ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Softener (D)	0.2	kg	As D.Softener	Sandin, Roos, et al. (2019)
Wetting/penetrating agent, synthetic	0.01	kg	see F. Wetting/penetrating agent	Sandin, Roos, et al. (2019)
Electricity (Combined for dyeing and finishig)	1.5	kWh	Fictional electricity mix	Sandin, Roos, et al. (2019)
Heat (Combined for dyeing and finishing)	38	MJ	heat production, light fuel oil, RoW ecoinvent38 APOS	Sandin, Roos, et al. (2019)
Transport of goods (By truck)	0.280	tkm	market for transport, freight, lorry, unspecified, RoW, ecoinvent38 APOS	Dinkel et al. (2007)

Table 7.25: Modelling of apparel production.

Same as cotton apparel production

Table 7.26: Modelling of distribution.

Same as cotton distribution

Table 7.27: Modelling of use phase.

Same as cotton use phase

Table 7.28: Model of separate collection and pre-sorting.

Same as cotton separate collection and pre-sorting

Table 7.29: Model of sorting at European sorting center.

Same as cotton sorting at European sorting center.

Table 7.30: Model of chemical recycling.

Outputs	Quantity	Unit	Dataset	Reference
Dimethyl terephthalate (DMT)	0.621	Kg		Schmidt et al. (2016)
Ethylene glycol (EG)	0.279	Kg		Schmidt et al. (2016)
EG for reuse in coumpounding	0.09	kg		Schmidt et al. (2016)
Waste to incineration	0.1	kg	treatment of municipal solid waste, incineration, RoW, ecoinvent38 APOS	Schmidt et al. (2016)
Inputs	**Quantity**	**Unit**	**Dataset**	**Reference**
Sorted textile waste	1.00	kg		Schmidt et al. (2016)
EG	0.10	kg	market for ethylene glycol, GLO, ecoinvent38 APOS	Schmidt et al. (2016)
Catalyst (NaCO3)	0.0005	kg	market for sodium bicarbonate, GLO, ecoinvent38 APOS	Schmidt et al. (2016)
Methanol	0.10	kg	market for methanol, GLO, ecoinvent38 APOS	Schmidt et al. (2016)
Thermal energy from light fuel oil (LFO)	13.80	MJ	heat production, light fuel oil, at boiler 10kW, non-modulating, RoW, ecoinvent38 APOS	Schmidt et al. (2016)
Thermal energy from natual gas	3.46	MJ	heat production, natural gas, at boiler atmospheric non-modulating ¡100kW, RoW, ecoinvent38 APOS	Schmidt et al. (2016)
Transport of goods (By truck)	0.311	tkm	market for transport, freight, lorry 7.5-16 metric ton, EURO6, RER, ecoinvent 38 APOS	Google Maps (n.d.)
Transport of goods (Sea)	21.1	tkm	market for transport, freight, sea, container ship, GLO, ecoinvent 38 APOS	Sea-Distances.org (n.d.)
Transport of goods (By truck)	0.25	tkm	market for transport, freight, lorry, unspecified, RoW, ecoinvent 38 APOS	Dinkel et al. (2007)

Table 7.31: Model of Re-granulation.

Outputs	Quantity	Unit	Dataset	Reference
PET granulate	1.000	kg		Ecoinvent
average incineration residue	0.0004	kg	market for average incineration residue, RoW, ecoinvent 38 APOS	Ecoinvent
Hazardous waste	0.0001	kg	market for hazardous waste, for underground deposit, RoW, ecoinvent 38 APOS	Ecoinvent
Municipal solid waste	0.001	kg	market for municipal solid waste, RoW, ecoinvent 38 APOS	Ecoinvent
waste plastic, mixture	0.002	kg	market for waste plastic, mixture, RoW, ecoinvent 38 APOS	Ecoinvent

Table 7.32: Model of Re-granulation (continue).

Inputs	Quantity	Unit	Dataset	Reference
Purified terephthalic acid	0.875	kg		Ecoinvent
ethylene glycol	0.334	kg		Ecoinvent
nitrogen, liquid	0.030	kg	market for nitrogen, liquid, RoW, ecoinvent 38 APOS	Ecoinvent
Electricity	0.194	kWh	market group for electricity, medium voltage, CN, ecoinvent 38 APOS	Ecoinvent
Steam	0.940	kg	market for steam, in chemical industry, RoW, ecoinvent 38 APOS	Ecoinvent
Heat	1.630	MJ	market for heat, district or industrial, other than natural gas, RoW, ecoinvent 38 APOS	Ecoinvent

7.2 LCIA results

This section represents the absolute value of LCIA results across the studied impact categories and scenarios for both cotton and polyester cases.

Table 7.33: LCIA results of both linear and recycling product system for cotton case.

	Climate change (kg CO2-eq)		Ecotoxicity (CTUe)		Land use (m2*a crop-eq)		Water use (m3)		Energy use (MJ-eq)	
Life cycle stages	Linear product system	Recycling product system	Linear product system	Recycling product system	Linear product system	Recycling product system	Linear product system	Recycling product system	Linear product system	Recycling product system
Primary fibre production	1.70E+00	1.47E+00	1.95E+01	1.68E+01	2.09E+00	1.80E+00	1.39E+00	1.20E+00	2.71E+01	2.34E+01
Yarn production	1.20E+00	1.20E+00	1.94E-01	1.94E-01	1.30E-02	1.30E-02	3.49E-03	3.49E-03	1.34E+01	1.34E+01
Fabric production	1.77E-01	1.77E-01	3.96E-02	3.96E-02	2.33E-03	2.33E-03	6.43E-04	6.43E-04	2.28E+00	2.28E+00
Wet processing	1.84E+00	1.84E+00	8.06E-01	8.06E-01	1.04E-02	1.04E-02	4.76E-02	4.76E-02	2.79E+01	2.79E+01
Apparel production	7.60E-01	7.60E-01	1.71E-01	1.71E-01	3.22E-02	3.22E-02	2.35E-03	2.35E-03	9.31E+00	9.31E+00
Distribution	7.16E-02	7.16E-02	5.51E-02	5.51E-02	1.81E-03	1.81E-03	1.28E-02	1.28E-02	2.75E+00	2.75E+00
Use phase	1.08E+00	1.08E+00	6.87E-01	6.87E-01	7.60E-02	7.60E-02	1.42E-02	1.42E-02	1.91E+01	1.91E+01
Incineration	2.90E-01	2.03E-01	3.73E-02	2.61E-02	4.08E-04	2.86E-04	3.73E-04	2.61E-04	2.34E-01	1.64E-01
Seperate collection & pre-sorting	0.00E+00	3.26E-03	0.00E+00	2.32E-03	0.00E+00	8.74E-05	0.00E+00	1.41E-04	0.00E+00	5.52E-02
Sorting	0.00E+00	2.18E-02	0.00E+00	1.38E-02	0.00E+00	5.27E-04	0.00E+00	3.76E-05	0.00E+00	2.63E-01
Mechanical recycling	0.00E+00	3.24E-02	0.00E+00	9.84E-03	0.00E+00	3.09E-04	0.00E+00	4.54E-05	0.00E+00	2.69E-01
Total	7.12E+00	6.85E+00	2.15E+01	1.88E+01	2.22E+00	1.94E+00	1.47E+00	1.28E+00	1.02E+02	9.89E+01

Table 7.34: LCIA results of linear and recycling product systems across five scenarios for cotton case.

	Linear product system	Recycling product system (Default)	Recycling product system (Higher collecion)	Recycling product system (Local sorting and recycling)	Recycling product system (Waste minimization)	Recycling product system (Pre-consumer waste recycling)
Climate change (kg CO2-eq)	7.12E+00	6.85E+00	6.72E+00	6.83E+00	6.23E+00	6.55E+00
Ecotoxicity (CTUe)	2.15E+01	1.88E+01	1.75E+01	1.88E+01	1.55E+01	2.42E+00
Land use (m2*a crop-eq)	2.22E+00	1.94E+00	1.79E+00	1.94E+00	1.59E+00	1.60E-01
Water use (m3)	1.47E+00	1.28E+00	1.18E+00	1.28E+00	1.05E+00	5.44E-02
Energy use (MJ-eq)	1.02E+02	9.89E+01	9.73E+01	9.86E+01	9.08E+01	1.01E+02

Table 7.35: LCIA results of both linear and recycling product system for polyester case.

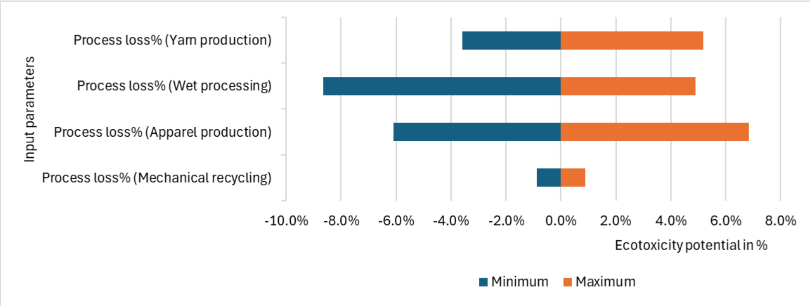
	Climate change (kg CO2-eq)		Ecotoxicity (CTUe)		Land use (m2*a crop-eq)		Water use (m3)		Energy use (MJ-eq)	
Life cycle stages	Linear product system	Recycling product system	Linear product system	Recycling product system	Linear product system	Recycling product system	Linear product system	Recycling product system	Linear product system	Recycling product system
Primary PET production	1.02E+00	8.76E-01	3.75E-01	3.21E-01	1.24E-02	1.06E-02	1.12E-02	9.55E-03	2.51E+01	2.15E+01
Fibre production	6.50E-01	6.50E-01	2.00E-01	2.00E-01	7.94E-03	7.94E-03	5.28E-03	5.28E-03	8.96E+00	8.96E+00
Yarn production	1.09E+00	1.09E+00	1.89E-01	1.89E-01	1.28E-02	1.28E-02	3.27E-03	3.27E-03	1.29E+01	1.29E+01
Fabric production	1.77E-01	1.77E-01	3.96E-02	3.96E-02	2.33E-03	2.33E-03	6.43E-04	6.43E-04	2.28E+00	2.28E+00
Wet processing	1.54E+00	1.54E+00	7.13E-01	7.13E-01	1.51E-02	1.51E-02	6.48E-03	6.48E-03	2.19E+01	2.19E+01
Apparel production	7.60E-01	7.60E-01	1.71E-01	1.71E-01	3.22E-02	3.22E-02	2.36E-03	2.36E-03	9.31E+00	9.31E+00
Distribution	7.16E-02	7.16E-02	5.51E-02	5.51E-02	1.81E-03	1.81E-03	1.28E-02	1.28E-02	2.75E+00	2.75E+00
Use phase	1.08E+00	1.08E+00	6.87E-01	6.87E-01	7.60E-02	7.60E-02	1.42E-02	1.42E-02	1.91E+01	1.91E+01
Incineration	2.90E-01	2.03E-01	3.73E-02	2.61E-02	4.08E-04	2.86E-04	3.73E-04	2.61E-04	2.34E-01	1.64E-01
Seperate collection & pre-sorting	0.00E+00	3.26E-03	0.00E+00	2.32E-03	0.00E+00	8.74E-05	0.00E+00	1.41E-04	0.00E+00	5.52E-02
Sorting	0.00E+00	2.19E-02	0.00E+00	1.38E-02	0.00E+00	5.27E-04	0.00E+00	3.76E-05	0.00E+00	2.63E-01
Chemical recycling	0.00E+00	1.41E-01	0.00E+00	3.43E-02	0.00E+00	7.04E-04	0.00E+00	2.36E-04	0.00E+00	2.31E+00
Recycled PET production	0.00E+00	3.47E-02	0.00E+00	1.49E-02	0.00E+00	6.09E-04	0.00E+00	1.96E-04	0.00E+00	4.17E-01
Total	6.69E+00	6.66E+00	2.47E+00	2.47E+00	1.61E-01	1.61E-01	5.66E-02	5.55E-02	1.03E+02	1.02E+02

Table 7.36: LCA results both linear and recycling product systems across five scenarios for polyester case.

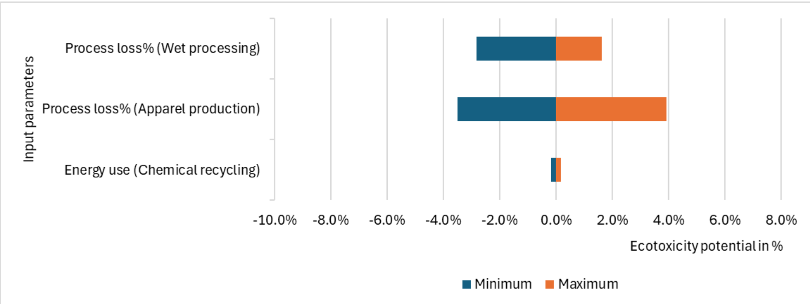
	Linear product system	Recycling product system (Default)	Recycling product system (Higher collecion)	Recycling product system (Local sorting and recycling)	Recycling product system (Waste minimization)	Recycling product system (Pre-consumer waste recycling)
Climate change (kg CO2-eq)	6.69E+00	6.66E+00	6.64E+00	6.58E+00	6.18E+00	6.55E+00
Ecotoxicity (CTUe)	2.47E+00	2.47E+00	2.47E+00	2.45E+00	2.32E+00	2.42E+00
Land use (m2*a crop-eq)	1.61E-01	1.61E-01	1.61E-01	1.65E-01	1.55E-01	1.60E-01
Water use (m3)	5.66E-02	5.55E-02	5.49E-02	5.60E-02	5.24E-02	5.44E-02
Energy use (MJ-eq)	1.03E+02	1.02E+02	1.02E+02	1.00E+02	9.41E+01	1.01E+02

7.3 Additional sensitivity analysis results

This section highlights the results for the sensitivity analysis for four impact categories: ecotoxicity, land use, water use and energy use.

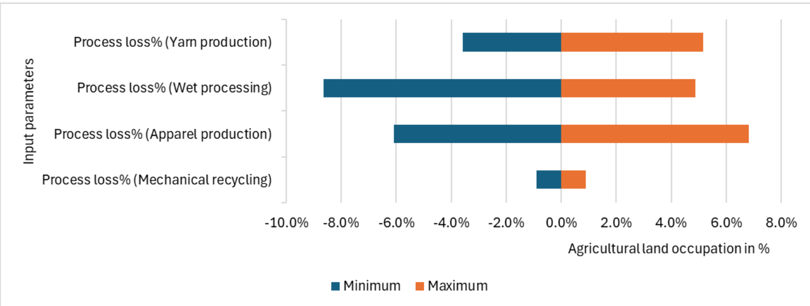


(a) Cotton case.

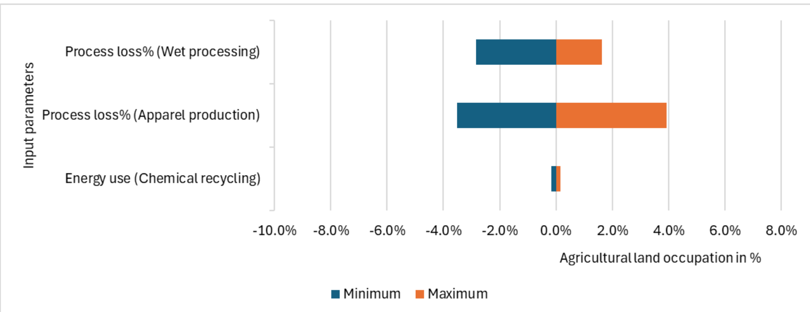


(b) Polyester case.

Figure 7.1: Sensitivity analysis of different parameters on ecotoxicity impact compared of recycling product system in (a) cotton and (b) polyester cases.

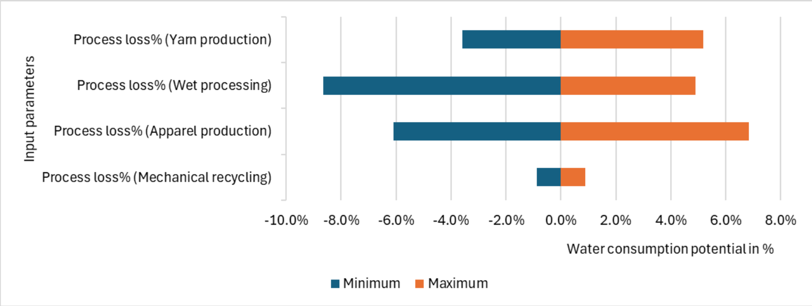


(a) Cotton case.

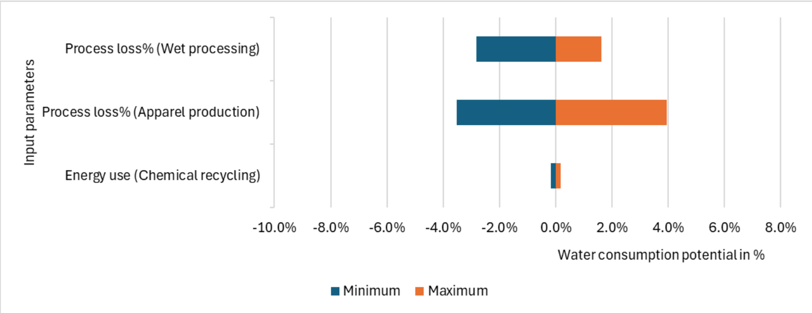


(b) Polyester case.

Figure 7.2: Sensitivity analysis of different parameters on land use impact of default recycling product system in (a) cotton and (b) polyester cases.

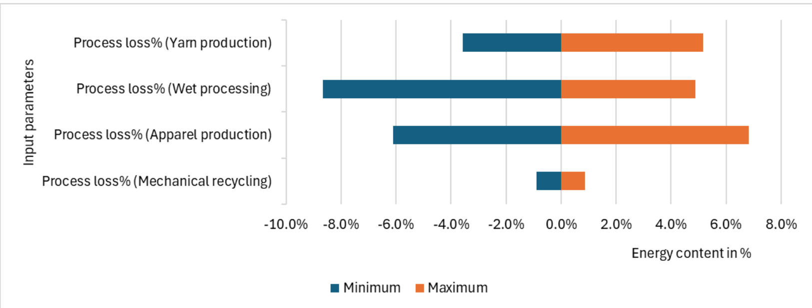


(a) Cotton case.

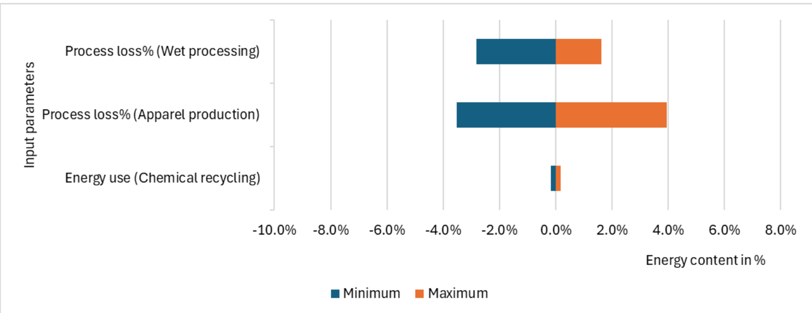


(b) Polyester case.

Figure 7.3: Sensitivity analysis of different parameters on water use impact of default recycling production system in (a) cotton and (b) polyester cases.



(a) Cotton case.



(b) Polyester case.

Figure 7.4: Sensitivity analysis of different parameters on energy use impact of default recycling production system in (a) cotton and (b) polyester cases.

7.4 Additional MFA results

This section presents quantified MFA models for the linear product system in the polyester case, as well as the recycling product system for cotton and polyester t-shirts consumed at the country level.

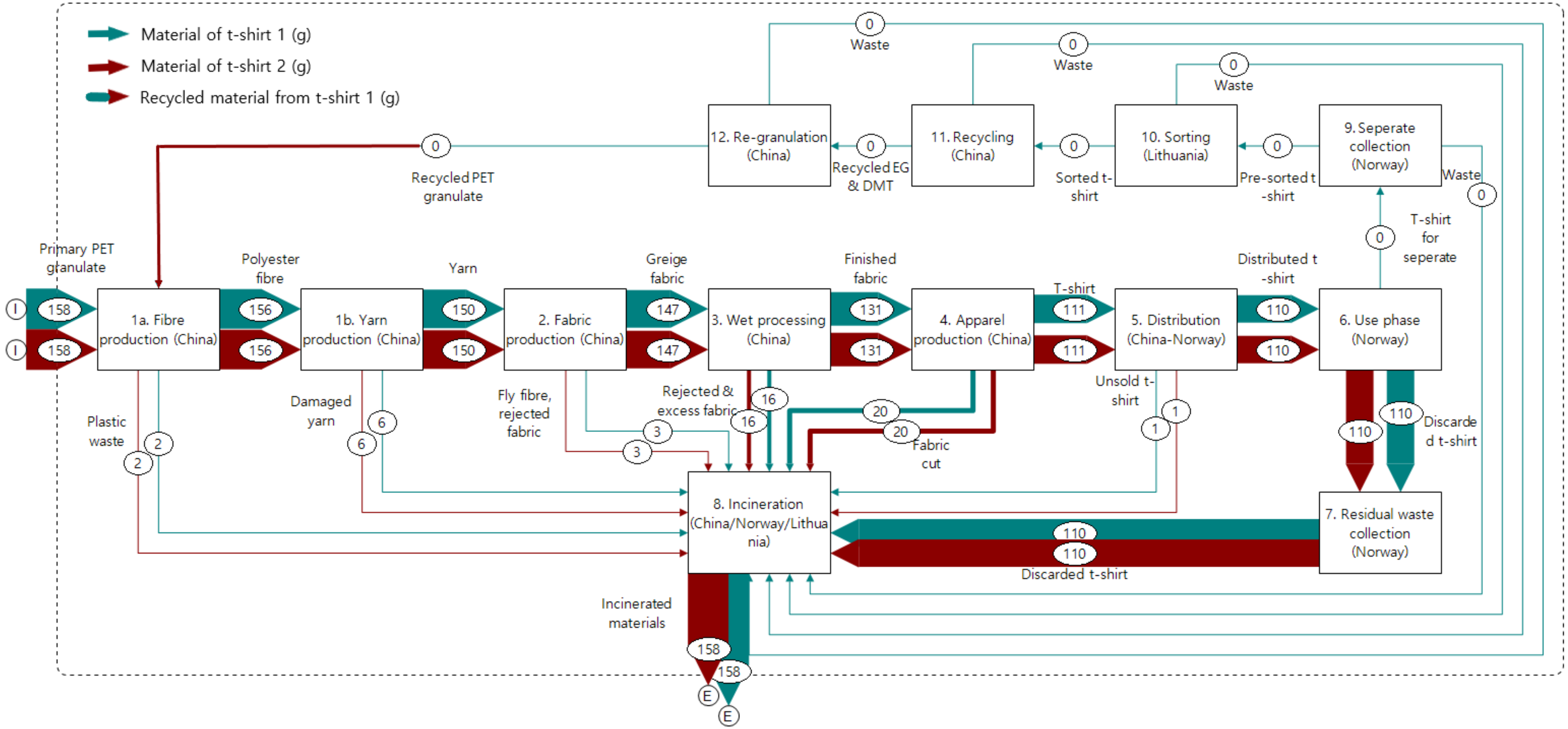


Figure 7.5: Material flows of two t-shirts over two consecutive lifecycles in the polyester linear product system.

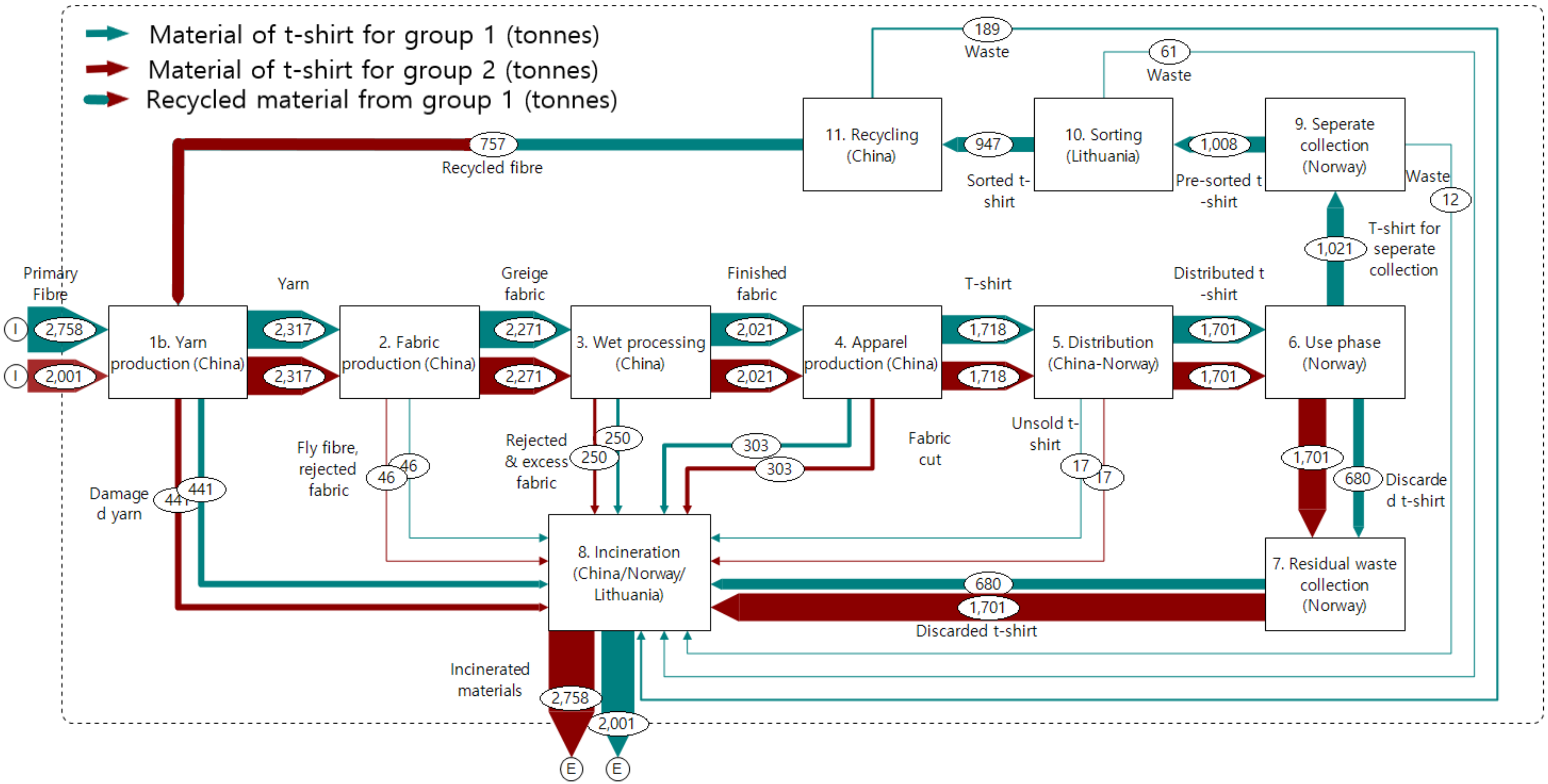


Figure 7.6: Material flows of two groups of t-shirts based on annual cotton t-shirt consumption of Norwegian households following recycling product system.

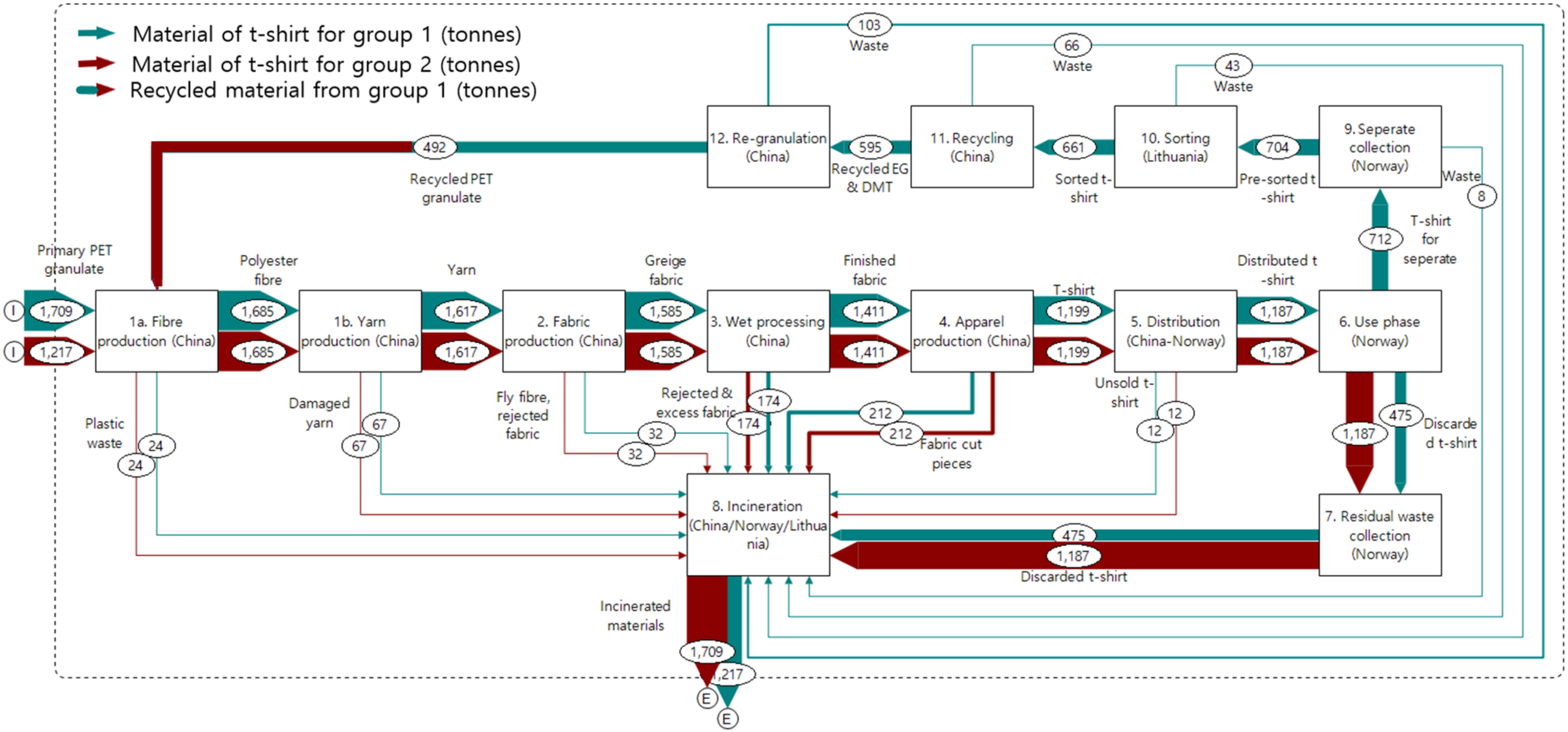


Figure 7.7: Material flows of two groups of t-shirts based on annual polyester t-shirt consumption of Norwegian households following recycling product system.

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