Master's thesis

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

Mari Brusletto Berntsen

LCA of polyester textile waste recycling using thermo-mechanical and thermo-chemical processes

Master's thesis in Nordic Master in Environmental Engineering with a specialisation in Residual Resources Enginering and Industrial Ecology.
Supervisor: Anders Damgaard and Johan Berg Pettersen.
Co-supervisor: Heather Logan
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Mari Brusletto Berntsen

Student number DTU: s232373
Studnet number NTNU: 510229

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Master's thesis in Environmental Engineering

Supervisor: Anders Damgaard
Co-supervisor: Heather Logan

Department of Environmental and Resource Engineering
Technical University of Denmark

Danmarks Tekniske Universitet

Master's thesis in Industrial Ecology

Supervisor: Johan Berg Pettersen

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

NTNU

Abstract

Global textile fibre production has increased over the last few decades. This increase, combined with the prevailing linear economic model of take, make, waste, has contributed to a significant increase in textile waste, with less than 1% being recycled into similar quality applications and the majority ending up in landfill or incineration. This forms the basis of this study and the aim is to understand how recycling can be a viable waste management option for textile waste. This study focuses on one method of textile recycling, namely polymer recycling, with particular emphasis on the emerging recycling technologies of thermomechanical and selective dissolution.

The investigation of these technologies identified gaps in the literature, including the under-researched nature of polymer recycling, the complexity of textile waste, and the critical role of the substitution ratio in recycling outcomes. Through a literature review and a comprehensive evaluation methodology, this study assesses the advantages, disadvantages and performance of thermomechanical and selective dissolution technologies in the management of textile waste.

A SWOT analysis, coupled with process mapping, flow assessment and a comparative life cycle assessment, was used to evaluate these technologies against current treatment options. The SWOT analysis shows clear advantages and disadvantages: TM is efficient and cost-effective, but struggles with polymer degradation and energy consumption; SD is good at removing contaminants and efficiently recovering output, but is hindered by high operating costs and significant environmental impacts. Both technologies require high quality feedstocks to effectively produce high quality outputs.

Comparative LCA results show that both thermomechanical and selective dissolution provide environmental savings in most impact categories, with notable reductions in climate change impacts. Thermomechanical and selective dissolution result in net savings of -334.29 and -341.72 kg CO2-eq per tonne of textile waste treated, respectively. This compares to 78.17 kg CO2-eq for the current treatment option. Despite the favourable results, the LCA also shows the significant influence of the dissolution process in the SD technology and the recovery process in both systems on their environmental performance.

Although thermomechanical and selective dissolution recycling technologies offer promising alternatives for reducing the impact of textile waste, further research is needed to improve the results of this study. The complexities associated with textile waste and the critical influence of the substitution ratio require further research to refine these technologies and to inform decision makers. This is particularly important given the transition to a circular economy model that emphasises reduce, reuse and recycle.

Sammendrag

Global tekstilfiberproduksjon har økt de siste tiårene. Denne økningen, kombinert med den lineære økonomimodellen basert på bruk og kast, har bidratt til en betydelig økning i tekstilavfall. Mindre enn 1% av dette avfallet blir resirkulert til produkter av lignende kvalitet og flertallet havner på deponi eller til forbrenning. Dette danner grunnlaget for denne studien, og målet er å forstå hvordan resirkulering kan være et bærekraftig avfallshåndteringstiltak for tekstilavfall. Denne studien fokuserer på én metode for tekstilresirkulering, nemlig polymerresirkulering, med særlig vekt på de fremvoksende resirkuleringsteknologiene termomekanisk og selektiv oppløsning.

Undersøkelsen av disse teknologiene tar for seg identifiserte mangler i litteraturen. Dette inkluderer kompleksiteten til tekstilavfall, at polymerresirkulering er lite utforsket, og den kritiske rollen substitusjons raten har på resultatene av resirkuleringen. Gjennom litteratursøk og en omfattende evalueringsmetodikk vurderer denne studien fordeler, ulemper og ytelse av termomekanisk og selektiv oppløsningsteknologi i håndtering av tekstilavfall.

En SWOT-analyse, sammen med kartlegging av prosesser og material strømmer, og en sammenlignende livssyklusanalyse, ble brukt for å evaluere disse teknologiene mot nåværende behandlingsalternativer. SWOT-analysen viser klare fordeler og ulemper: termomekanisk resirkulering er både effektivt og kostnadseffektivt, men sliter med polymerdegradering og energiforbruk; selektiv oppløsnings resirkulering er god til å fjerne uønskede fibre eller materialer og kan effektiv gjenvinne fibre, men hindres av høye driftskostnader og betydelige miljøpåvirkninger. Begge teknologiene krever en input av fibre med høy kvalitet for å effektivt kunne produsere fibre med høy kvalitet.

Resultater fra den sammenlignende LCA-en viser at både termomekanisk og selektiv oppløsnings resirkulering gir miljøbesparelser i de fleste påvirkningskategorier, med merkbare reduksjoner i påvirkningskategorien som omhandler klima forandringer. Termomekanisk og selektiv oppløsning resirkulering resulterer i netto besparelser på henholdsvis -334,29 og -341,72 kg CO2-ekvivalenter per tonn behandlet tekstilavfall. Dette sammenlignes med 78,17 kg CO2-ekvivalenter for nåværende behandlingsalternativ. Til tross for de gunstige resultatene, viser LCA-en også den betydelige innflytelsen av oppløsningsprosessen i den selektive oppløsningsteknologien og gjenvinningsprosessen i begge teknologiene på deres miljøprestasjon.

Selv om termomekanisk og selektiv oppløsningsteknologi tilbyr lovende alternativer for å redusere miljøpåvirkningen fra tekstilavfall, er ytterligere forskning nødvendig for å forbedre resultatene av denne studien. Kompleksiteten forbundet med tekstilavfall og den kritiske innflytelsen av substitusjons raten krever ytterligere forskning for å forbedre disse teknologiene og informere beslutningstakere. Dette gjelder spesielt med tanke på overgangen til en sirkulær økonomimodell som understreker reduksjon, gjenbruk og resirkulering.

Preface

This thesis is the final project of the Nordic Master in Environmental Engineering with specialisation in Residual Resources and Industrial Ecology. The thesis is written by Mari Brusletto Berntsen, who is a master student in the Nordic Five Tech (N5T) program between the Technical University of Denmark (DTU) and the Norwegian University of Science and Technology (NTNU). The thesis is written as a project for the Department of Environmental and Resource Engineering (DTU Sustain) at DTU and the Department of Energy and Process Engineering at NTNU. The Master's thesis is worth 30 ECTS and is written during the spring semester 2024 - from January 2 to June 2. The Master's thesis is supervised by Anders Damgaard (Associate Professor, Department of Environmental and Resource Engineering), Johan Berg Pettersen (Associate Professor, Industrial Ecology Programme Department of Energy and Process Engineering) and co-supervised by Heather Logan (Postdoc, Department of Environmental and Resource Engineering).

The basis of the study was a desire to explore some of the possibilities for improving the circularity of textiles and how recycling can contribute to this improvement. The focus was on a specific method of textile waste recycling and the study included a thorough review of existing literature on emerging technologies within this recycling method. A comparative Life Cycle Assessment was then carried out to evaluate these emerging recycling technologies against current treatment options.

Given the increasing use and importance of Artificial Intelligence (AI), it's worth noting that this study used AI, specifically ChatGPT, to correct spelling and grammar, but not for any other purpose.

Throughout this Master's thesis, I am extremely grateful for the support and guidance provided by my supervisors. My sincere thanks go to Heather, Anders and Johan for their invaluable interest, guidance, support, patience and advice throughout the project. Their insights have been instrumental in the completion of this project and have motivated me greatly. I would also like to thank my family, friends, and boyfriend for their constant support and words of encouragement throughout this study.

København, June 2, 2024

Mari Brusletto Berntsen

Mari Brusletto Berntsen

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List of Abbreviations

Abbreviation	**Meaning**
AC	Acidification
APOS	Allocation at the point of substitution
BAU	Business As Usual
C	Completeness
CC	Climate change
DQR	Data Quality Ratio
ECF	Ecotoxicity freshwater
EF	Eutrophication, freshwater
EM	Eutrophication, marine
ET	Eutrophication, terrestrial
EU	European Union
FTc	Further Technological Correlation
FU	Funtional Unit
Gc	Geographic Correlation
GHG	Greenhouse gas
HTC	Human toxicity, cancer
HTNC	Human toxicity, non-carcinogenic
IR	Ionising radiation
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LU	Land use
MFA	Material Flow Analysis
NMMO	N-methylmorpholine N-oxide
OD	Ozone depletion
OJ	Official Journal
PA	Polyamide
PE	Personal equivalent
PET	Polyethylene Terephthalate
PM	Particulate matter
POF	Photochemical ozone formation
PP	Polypropylene
R	Reliability
RQ	Research Question
RUEC	Resource use, energy carrier
RUMM	Resource use, minerals and metals
SD	Selective Dissolution
SR	Sensitivity Ratio
SWOT	Strengths, Weaknesses, Opportunities, Threats
Tc	Temporal Correlation
TM	Thermomechanical
TS	Total Solids
WU	Water use

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1 Introduction

Textile production has increased globally over the past decades, and textile manufacturers today have roughly doubled their production volumes since the early 2000s (Crestani et al., 2023). Every year, 53 million tonnes of textile fibres are produced (Loo et al., 2023), and the global demand for textile products continues to grow. This trend is set to continue due to rapidly changing fashion trends, increased consumer purchasing power and population growth (Loo et al., 2023). The industry has adopted a business model based on selling large volumes of short-lived clothing, contributing to what is known as a linear business model (Köhler et al., 2021). At the same time, the textile industry faces major environmental and resource challenges (Sandin and Peters, 2018).

According to the European Commission's Circular Economy Action Plan (Commission and Communication, 2020), textiles are the world's fourth most resource-intensive category in terms of primary raw materials and water consumption. It is also the world's fifth most polluting industry in terms of greenhouse gas (GHG) emissions. This will continue to rise as demand for textiles grows. Increased consumption of textiles will further increase the amount of textile waste generated. In the European Union (EU) the annual amount of discarded textiles is estimated to be 5.8 million tonnes (Zamani et al., 2015). With an EU population of 448 million people, this amount of textile waste is equivalent to 13 kg of textile waste per person per year. Despite this significant volume, the treatment of these textiles remains largely inefficient: less than 1% is recycled and made into similar quality applications, 12% is recycled into lower quality applications through downcycling, while the remaining 73% is mostly landfilled or incinerated (Phan et al., 2023).

Due to environmental concerns, the importance of managing textile waste from end-of-life or post-consumer products and the need to conserve finite resources has increased the search for strategies to reduce textile waste and divert it from landfills (Loo et al., 2023). It is necessary to transform the economic system from a linear system based on take, make and waste to a circular system based on reduce, reuse and recycle (Bianchi et al., 2023).To work towards this transition, the European Union's Waste Framework Directive, OJ L312/10 European Parliament (2008), introduced the waste hierarchy. The waste hierarchy illustrates the preferred approach for waste management strategies and an illustration can be found in Figure 1. The hierarchy suggests prevention first, then preparation for re-use, followed by recycling, recovery such as energy recovery, and finally disposal.

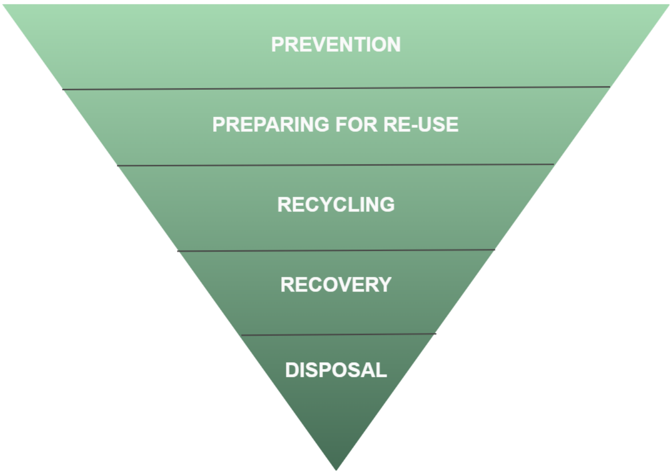

Figure 1: Illustration of the waste hierarchy. Inspired by the European Union Waste Framework Directive (European Parliament, 2008).

The waste hierarchy suggests that the best way to manage discarded textiles is to reuse them. However, when textiles are damaged or unsuitable for reuse, it's crucial to develop recycling technologies to handle them effectively. Recycling therefore plays a key role in the textile industry's transition to a circular and low-carbon economy (Loo et al., 2023).

In an attempt to change today's textile waste management, the Directive OJ L150/129 form the European Parliament (2018) requires a separate collection of textile waste for all EU member states by January 1, 2025. This regulation leads to a potential increase in the amount of textiles available for either reuse or recycling in both Europe and Denmark. In addition, the European Commission's Circular Economy Action Plan aims to extend producer responsibility through regulatory measures and to encourage industrial applications to promote the sorting, reuse and recycling of textiles (Commission and Communication, 2020). This regulatory landscape underlines the need for effective textile waste management. Therefore, this study focuses on emerging recycling technologies and assesses their potential compared to conventional disposal methods, as well as their environmental impact. The following section outlines the objectives and research questions of this study.

1.1 Objective and research questions

This study is being conducted to address the issues related to textile waste and to gain a clearer insight into the knowledge gaps, challenges and opportunities in this area - ultimately aiming to understand how recycling can be a viable waste management option for textile waste.

The objective of this study is to investigate a method of textile recycling, more specifically polymer recycling, and compare this to the current treatment method. This will be done through an in-depth and comprehensive review of recent developments, with a particular focus on emerging technologies within this recycling method. The technologies are further explored by mapping the processes relevant to the treatment and investigate how the material flows through the system. Based on the process mapping and flow assessment, the environmental impact can be assessed through a comparative Life Cycle Assessment (LCA), and an identification of the substitution rate. These objectives are outlined in the following research questions (RQ):

RQ1: What are the emerging technologies for recycling polyester fibres within the polymer recycling method?

To answer this question, an in-depth and comprehensive review of the literature and existing research on technologies within the polymer recycling method will be carried out. The technologies will be further investigated through a SWOT analysis to evaluate the performance, advantages and disadvantages of the technologies.

RQ2: What is the environmental impact of recycling polyester fibres using the identified emerging polymer recycling technologies compared to the current treatment method?

This will be investigated by identifying the key processes for the technologies through process mapping and flow assessment. This will be followed by a comparative LCA to assess the environmental impacts of the technologies and the current treatment method. In Denmark the current treatment method is downcycling and incineration.

RQ3: Within the identified emerging polymer recycling technologies, what is the recovery rate for polyester fibres?

This will be investigated through the LCA conducted and evaluated by looking at how the systems perform and how the quality of recycled polyester material compares to virgin polyester material.

2 Background

This chapter provides an overview of the textile supply chain and explores the integration of textile recycling as a viable waste management option. It addresses the importance of textile waste recycling and provides key insights into polymer recycling by highlighting emerging recycling technologies. Finally, it identifies existing gaps in the literature on textile waste recycling.

2.1 Relevant terminology

To ensure clarity and avoid misunderstandings, it is important to define the terminology used throughout this study. Table 1 provides a comprehensive overview of these important terms and their definitions.

Table 1: Overview of relevant terms used in this study and their definitions.

Terms	**Definition**
Man-made fibres	Fibres that are either synthetic or artificial based. Examples include polyester, elastane, and viscose (Bianchi et al., 2023).
Natural fibres	Fibres that are either animal, vegetable or mineral based. Examples include wool, silk and cotton (Bianchi et al., 2023).
Findings	One or more items used, for example, to fasten or close a garment. It may be added to the textile during manufacture or during use. Examples are zippers or buttons.
Post-consumer	Textiles that have been used by consumers and are now discarded or disposed of.
Textile waste	End-of-life textiles that are stained, perforated, worn or otherwise damaged. Examples of textiles included in this definition are clothing, curtains and towels. Bags, belts and shoes, as well as reusable clothing and textiles, are not included in the definition of textile waste (Miljøministeriet, 2021).
Impurities	Unwanted substances in the textile waste stream that contaminate the output.
Polyester	A synthetic man-made textile fibre. A textile product made of polyester fibres usually refers to textiles made of PET (polyethylene terephthalate) (European Commission et al., 2021).
Pure fibres	Is in this report referred to as textiles containing only the polyester fibre type.
Blended fibres	In this report referred to as the textiles containing a blend of polyester and other fibre types.
Other fibres	In this report referred to fibres other than the polyester fibres.
Other fibres recyclable	In this report referred to fibres other than polyester fibres that are of sufficient quality to be downcycled rather than incinerated.
Polymer	A large molecule made up of many monomers (The Editors of Encyclopedia Britannica, 2024)

2.2 Textile supply chain

Textiles are classified as a necessity in the everyday life of a human being (Yalcin-Enis et al., 2019). The European Parliament and Council (2011) defined textiles as “any raw, semi-worked, worked, semi-manufactured, manufactured, semi-made-up or made-up product” Trzepacz et al. (2023, p.6), which regardless of the mixing or assembly process employed, is exclusively composed of textile fibres. In addition, products containing at least 80% textile fibres by weight are also considered textile products(Trzepacz et al., 2023).

When a textile product is produced, the activities in the supply chain are often presented as linear, from raw material to disposal. The supply chain for textile production can be divided into the main stages illustrated in Figure 2. There are many sub-stages within these eight stages, but these represent the main supply chain.

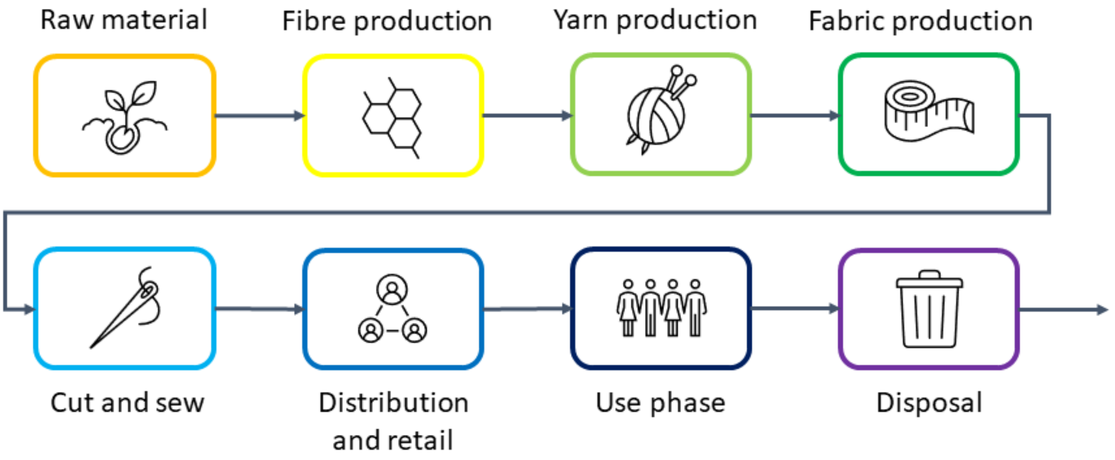

Figure 2: Illustration of the textile production supply chain and its main stages. Different colours represent different stages in the production process. The illustration is inspired by Crestani et al. (2023).

A textile can be made up of different types of fibres and there are several ways of classifying textile fibres. The most commonly used classification is based on the resources and origin of the fibres, leading to the current classification of fibres as either man-made or natural (Bianchi et al., 2023). Depending on the type of textile fibre to be produced, the raw materials can be harvested if it is a natural fibre, or manufactured if it is a man-made fibre. I 2018, the main fibres used in the textile industry were polyester and cotton, accounting for 51% and 25% respectively (Niinimäki et al., 2020). About 60% of the fibres produced worldwide are destined for the fashion industry (Niinimäki et al., 2020).

Once fibres have been produced, they are ready to be spun into yarn. Yarn is made by twisting fibres together to form a continuous thread that can be used to make fabric. Yarn can be made by a number of different processes, such as spinning or twisting. Yarn can be used to make fabric, which is the main material used to make textiles. The yarn is either knitted or woven in the process of making fabric (Crestani et al., 2023). Fabric goes through several processes before it becomes the final textile product. The most common steps are dyeing, bleaching, printing and wet processing. The fabric is then cut, sewn, finished and packaged for distribution and retail (Crestani et al., 2023). In the textile supply chain, the stages that follow production are the use of the textile and finally its disposal.

This study focuses specifically on what happens during the disposal phase of textiles. Extending the supply chain to include reuse and recycling after disposal would create loops in what is currently a linear process, shifting the model towards a circular supply chain. In this study, disposed textiles are referred to as textile waste and follow the definition of textile waste from the Danish online legal information system, Retsinformation, which defines textile waste as end-of-life textiles that are stained, perforated, worn or otherwise damaged. Examples of textiles included in this definition are clothing, curtains and towels. Bags, belts and shoes, as well as reusable clothing and textiles, are not included in the definition of textile waste (Miljøministeriet, 2021).

2.3 Recycling supply chain

One effective approach to manage textile waste is recycling, which according to the EU Waste Framework Directive is defined as: "any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes" (Huygens et al., 2023, p.6).

Textile recycling processes can be classified in various ways, with no single method being universally accepted. The classification is based on the fact that recycling processes involve a number of process steps, leading to a broad categorisation of textile recycling methods as mechanical, chemical and thermal (Riemens et al., 2021). Mechanical recycling uses physical forces and can be used as a precursor to chemical or thermal recycling. It can also be used independently to recycle fabrics or fibres directly. Chemical recycling uses chemical reactions or dissolution techniques to recover polymers or monomers. Thermal recycling uses heat to recover polymers or monomers and should not be confused with energy recovery processes (European Commission et al., 2021). Although this classification indicates which process in the recycling process that is the main recycling process, it can be very confusing and a simplification of reality. It is a simplification because recycling routes often consist of a mixture of these processes. (Sandin and Peters, 2018).

Instead of classifying the recycling routes according to the processes involved, another classification is based on the type of materials recovered and their level of disassembly (Sandin and Peters, 2018), with each level capturing a different material value (Ellen MacArthur Foundation, 2017). These classifications include recycling at different levels, such as fabric, fibre, polymer, oligomer and monomer recycling. These are the classifications used in this study.

To address the growing challenge of textile waste and promote sustainable resource use, the traditional linear textile production supply chain can be extended to include reuse, recycling and recovery. In this way, the chain does not end at disposal, but allows textile waste to flow into various treatment options. An illustration of this extension is shown in Figure 3.

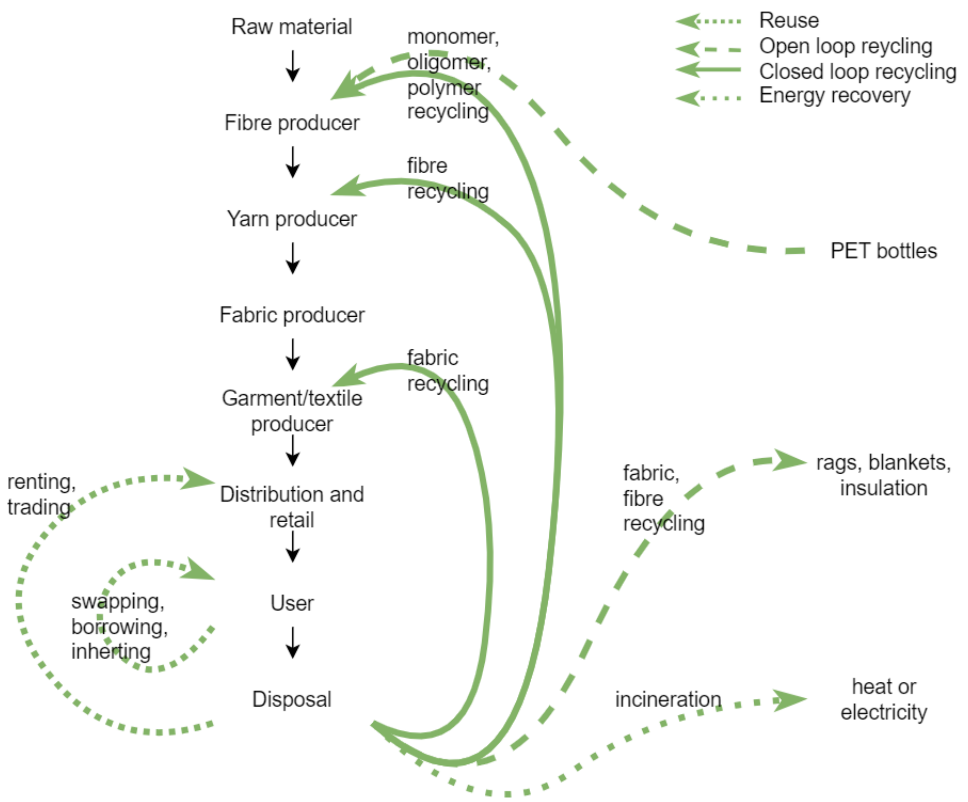

Figure 3: Illustration of textile reuse and recycling routes. The different types of arrows illustrate the difference between reuse, open- and closed-loop recycling and energy recovery. The figure is adapted from (Sandin and Peters, 2018).

The figure shows different treatment options for discarded textiles after their use phase. On the left, the arrows of small dotted lines indicate that textiles can be reused through swapping, borrowing, inheriting, or renting and trading. Reuse is considered by the waste hierarchy to be the most effective method of managing discarded textiles, as it extends their life cycle without the need for additional reprocessing.

The small dotted line at the bottom right of the figure indicates energy recovery, the third preferred waste treatment option after recycling. In this case, the textile materials are not recycled but incinerated to produce electricity or heat. Although energy recovery utilises the energy content of the waste, it does not preserve the material value, making it a less desirable option according to the waste hierarchy.

The dashed lines on the right side represent open-loop recycling and downcycling processes, showing how textile waste interacts with external resources or sectors. Open-loop recycling is when recycled material is used in a different type of product than the original recycled product. Downcycling is when the recycling material is of lower quality or value than the original product. (Sandin and Peters, 2018). For example, the arrow for polyethylene terephthalate (PET) bottles shows how non-textile materials can be converted into fibres for textile production, rather than being recycled within their own material cycle. This illustrates open-loop recycling, where materials such as thermoplastic PET bottles are integrated into different product cycles.

Conversely, the arrow leaving the supply chain marked with rags, blankets and insulation highlights downcycling, where textile waste is converted into products of lower quality or value than the original materials. Downcycling is the most common form of recycling used today (Sandin and Peters, 2018).

On the right side of the supply chain, solid arrows indicate different methods of closed-loop recycling, where textile materials are recycled into new fibres for new textile products of similar or identical quality. Closed-loop recycling involves converting textile waste back into fibres that are then used to make new textiles, keeping the material within the same product loop (Sandin and Peters, 2018). An example of closed-loop recycling is when the fibres from a T-shirt, for example, are recycled into new fibres to make a new T-shirt or another textile product. Table 11 in Appendix A provides an overview of these closed-loop recycling methods including their definition, maturity, advantages and disadvantages.

2.4 Purpose of textile waste recycling

Having introduced the basics of how the textile supply chain works and how recycling can be integrated into this supply chain, it is important to look at some of the purposes of recycling textile waste.

The most common waste management options for textile waste are disposal by incineration or landfill. These common disposal methods have limited effectiveness and are the least preferred treatment options according to the waste hierarchy (European Parliament, 2008). Despite their prevalence, these methods contribute significantly to resource depletion and environmental impacts, highlighting the need for more sustainable practices such as recycling (Phan et al., 2023).

The textile industry is known for its high consumption of raw materials and water, and as a significant source of GHG emissions. It is therefore under increasing pressure to improve its sustainability practices (Commission and Communication, 2020). The environmental challenges posed by the textile industry are significant, including high greenhouse gas emissions, extensive water use and the use of harmful chemicals. It is estimated that in order to align with sustainable practices within planetary boundaries by 2025, the industry will need to reduce the impact of each garment used by 30-100% across different environmental impact categories (Sandin and Peters, 2018). As global demand for textiles continues to grow, so does the environmental impact and the volume of textile waste, making the development of effective recycling methods more important than ever (Loo et al., 2023).

Downcycling is currently the most common recycling method. However, its environmental benefits are limited due to the lower quality of the materials produced, which do not sufficiently replace the need for virgin resources (Sandin and Peters, 2018; Schmidt et al., 2016). Given that less than 1% of textile waste is currently recycled into similar quality applications, there is significant potential for improvement, particularly in polymer recycling. This process is suitable for textiles that cannot be reused or recycled by fabric or fibre recycling, and provides a means of diverting waste from incineration and landfill (Phan et al., 2023; Sandin and Peters, 2018). Therefore, it is important to explore new polymer recycling technologies and assess their environmental impacts to support the transition to a more circular economy, highlighting recycling as an important waste management option for discarded textile waste.

Addressing these challenges requires a combined approach, with recycling playing a key role. Environmental assessment tools such as Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) are crucial in evaluating the environmental benefits of different options for textile waste treatment and recycling (Sandin and Peters, 2018). This study uses MFA, which systematically assesses stocks and flows within a defined system (Brunner and Rechberger, 2016), combined with LCA, which assesses the environmental impacts of a product or system (International Organization for Standardization (ISO), 2006). By integrating a simple MFA based on process mapping and flow assessment with an LCA, this research aims to identify critical processes, track material flows and evaluate the environmental impact of polymer recycling technologies.

2.5 Polymer recycling

Fibre recycling is the most commonly used recycling method today. However,it often does not provide the fibre quality required to produce textiles made entirely from recycled fibres (Ellen MacArthur Foundation, 2017). Polymer recycling, on the other hand, breaks down both the textile fabric and its fibres, preserving the chemical structure of the polymer. A polymer is a large molecule made up of many monomers (Ellen MacArthur Foundation, 2017; The Editors of Encyclopedia Britannica, 2024). The recycling process is generally very effective and can reproduce material and achieve almost the same properties and quality as virgin material (Damayanti et al., 2021).

Although polymer recycling can produce materials with qualities almost identical to virgin materials, research shows that the polymer chain degrades with each recycling cycle (Damayanti et al., 2021). The quality of recycled polymers is also highly dependent on the condition of the input materials. In contrast, monomer and oligomer recycling can retain the material quality and properties of virgin fibres, and can potentially produce even higher quality fibres than polymer recycling. However, these processes involve more steps and consequently have higher energy and water consumption and costs (European Commission et al., 2021; Phan et al., 2023).

Polymer recycling methods are rapidly evolving and represent a significant advance in recycling technologies, although they are still in the early stages of development (Ellen MacArthur Foundation, 2017). Continued research is essential to improve the efficiency and effectiveness of this recycling method, with the aim of minimising polymer chain degradation through successive recycling processes.

2.5.1 Polymer recycling technologies

There exist different types of polymer recycling technologies, and among them are thermomechanical and selective dissolution recycling.

Thermomechanical

Thermomechanical (TM) recycling is a key method within the polymer recycling pathway, using both mechanical and thermal processes to recover polymers. For this reason, this recycling technology is often referred to as thermo-mechanical recycling (European Commission et al., 2021). The process involves heating thermoplastic materials until they melt, which then allows the recovery of polymers in the form of granules that can be re-spun into new fibres. This technology involves several key steps, including sorting by fibre type and colour, pre-treatment, shredding, grinding and melt extrusion (European Commission et al., 2021). Typically, this process is used to recycle pure synthetic fibres such as polyester, polyamide (PA) and polypropylene (PP), which require the input materials to be of a single or compatible polymer type to ensure high quality recycled polymers (Loo et al., 2023; European Commission et al., 2021).

Selective Dissolution

Selective dissolution (SD) is another polymer recycling technology. It involves the dissolution of fibres by chemical extraction, allowing the selective removal of fibres using appropriate solvents, while eliminating additives (Loo et al., 2023; Phan et al., 2023). This method is particularly advantageous when processing mixed fibre textiles as it can effectively isolate pure polymers. Under certain conditions, the use of a certain solvents can dissolve the desired polymers, which is useful for recycling blended fibre textiles such as polycotton blends (Phan et al., 2023). Polycotton blends are textiles with a fibre blend of polyester and cotton. Solvents used in this process include e.g. N-methylmorpholine N-oxide (NMMO), ionic liquids and caustic soda, which are effective in dissolving polyester from polycotton blends (Loo et al., 2023). In addition, selective dissolution can remove almost any contaminant, including dyes, improving the quality and usability of recycled polymers (European Commission et al., 2021). When this recycling technology is used to recycle synthetic fibres such as polyester, the polyester fibre remaining after the dissolution process can be sent to thermal processes to recover polymers. This is why the technology is often referred to as thermo-chemical (Sandin and Peters, 2018).

2.5.2 Fibres suited for polymer recycling

There are both natural and man-made polymers, and polymer recycling can be performed at several fibre types. At the molecular level, each type of fibre, whether man-made or natural, is made up of polymer chains. Each fibre type has specific monomer and polymer linkages that are identical to that fibre type. (Bianchi et al., 2023).

Although polymer recycling is versatile and can be applied to many fibre types, not all fibres are suitable for all recycling technologies. For example, TM recycling technology is specifically designed for pure synthetic fibres with a single or compatible polymer type. This technology is particularly suitable for thermoplastics, which are synthetic fibres that can be melted and reprocessed. Thermoplastics are polymeric materials that soften when heated and harden when cooled, consisting of linear molecular chains (Grigore, 2017). Common thermoplastics include PET, PA6 and PP, which are widely used in textiles. When a textile product is made of polyester, this usually refers to textiles made of PET (European Commission et al., 2021).

The growing interest in polymer recycling, particularly technologies that deal with synthetic fibres, stems from their dominance in the fibre market. Synthetic fibres such as polyester currently account for 54% of global fibre production. Other synthetics such as PA account for 5%, with PP, acrylics and elastane together accounting for a further 5.2% of the market (Phan et al., 2023). Polyester is the most widely used fibre in the textile industry today because of its low cost and excellent properties. (Damayanti et al., 2021).

Although polyester fibres are the dominant fibre type in the market, this doesn't mean that the total amount of polyester produced is exactly the amount of polyester that can be reused or recycled. One reason for this is that today's textiles are increasingly made from blended fibres to meet the demands of modern fashion. By combining the unique properties of different types of fibre, they offer enhanced functionality. For example, a small amount of elastane can add comfort to textiles, while a blend of polyester and cotton, combines comfort with strength and cost effectiveness. Polyester is cheaper than cotton, making polycotton an economical choice (Harmsen et al., 2021).

However, the diversity and complexity of textile waste poses significant recycling challenges. Textiles made from mixed fibres are particularly difficult to recycle because the fibres must be separated before they can be processed individually. Although various recycling technologies exist, they struggle to process blended fibres efficiently. For example, TM recycling often results in poor quality fibres, whereas technologies such as selective dissolution are more effective at extracting and recycling specific fibres from fibre blends (Loo et al., 2023; Phan et al., 2023).

The textile market is characterised by a wide variety of fibre blend combinations, which further complicates the recycling process. Improving separation technology and addressing technology gaps in the recycling of textile waste and blended fibres could significantly increase the amount of textiles recycled and reduce the amount incinerated or landfilled (Loo et al., 2023). In addition to the technological challenges of recycling, a major problem is the lack of reliable data on fibre composition. Technologies such as infrared sorting can help to identify the specific blends used in textile products (Harmsen et al., 2021).

2.6 Gaps in literature

While addressing the importance of recycling as a waste management option for textile waste, several factors influencing the quality and comprehensiveness of existing studies were identified. This led to the identification of notable gaps in the literature. These gaps in the literature are important to note as they could play a significant role in assessing the overall environmental impact of textile waste recycling. This section outlines some of these identified gaps, focusing on three main areas, which are described in detail below.

Little explored recycling method. The most widely used and researched form of textile recycling today is fibre recycling (Peters et al., 2019). Sandin and Peters (2018) reviewed 41 papers and found that fibre recycling is the most studied recycling method. It accounted for 57% of the studies, while 37% studied the polymer recycling method. Despite this, polymer recycling is not yet being applied at scale, making it difficult to know the details of the processes (Ellen MacArthur Foundation, 2017). Furthermore, the modelling of polymer recycling processes is sometimes based on old inventory data or very rough estimates. More detailed and updated primary inventory data, as well as more publicly available information on the processes, are particularly needed for polymer recycling technologies (Sandin and Peters, 2018).

Complexity of textiles. Although there is a wide variety of methods for recycling textiles, the complex and non-uniform nature of textile waste streams poses significant challenges and difficulties (Loo et al., 2023). Textiles are often made up of more than one type of fibre (Harmsen et al., 2021). In particular, textiles with a multi-material fibre composition complicate the recycling of textiles because the different fibres must first be separated in order to recycle the different fibres individually. Separating the different fibres requires specific recycling technologies (Loo et al., 2023). In addition, textiles are often made up of several components such as zips, buttons, prints, coatings and contaminants (Loo et al., 2023). Clothing and textiles can be labelled as 100% single material, yet they can contain small quantities of other materials (Ellen MacArthur Foundation, 2017).

Substitution rate. Many studies often assume that the input material to a recycling process is waste, which has no environmental impact, and that when the recycled material is used to make new products, the material is a substitute for equivalent virgin materials (Sandin and Peters, 2018). This substitution benefit depends on how much of the material is substituted. Most studies on textile recycling assume a substitution rate similar to 1 (100% substitution) without providing justification (Sandin and Peters, 2018). A 100% substitution rate implies that the recycled material can fully substitute the same amount of virgin or non-recycled material(Roos et al., 2019), thus fully accounting for the environmental credits associated with the recycling process. This is a problem as it reduces the reliability of the results of the environmental benefits of recycling (Sandin and Peters, 2018).

3 Methodology

This chapter outlines the methodology used in this study and provides a structured approach to its implementation. It begins with an overview of the research structure, presenting all the steps undertaken throughout the study. Subsequent sections provide an explanation of how each step within the research structure was carried out.

3.1 Research structure

The research for this study went through several stages as shown in Figure 4. Firstly, a brief literature review was carried out to select a textile recycling method. This was followed by a SWOT analysis of the emerging recycling technologies within the chosen method and the development of a case study to explore these recycling technologies as well as current textile waste treatment options. The next stage was to map the required processes and identify the key steps for polymer recycling of textile waste. A flow analysis was then carried out to identify where losses occur in the system and to investigate the recovery rate. The system was then modelled using EASETECH, a LCA software for modelling the assessment of environmental technologies. Finally, the results were analysed and interpreted. Each of these stages is discussed in more detail in this section.

Figure 4: The research structure of this study.

3.2 Literature review and SWOT analysis

A brief preliminary literature review was performed to determine the selection of a textile waste recycling method for further investigation. The level of maturity and the respective advantages and disadvantages of each recycling method shown in Table 11 in Appendix A form the basis for the selection of the recycling method.

The SWOT analysis in this project was carried out to understand the performance and feasibility of the different recycling technologies within the polymer recycling process. A SWOT analysis is a widely used method for analysing an organisation's resources and environment. It can also be used as a technology analysis tool to improve decision making. When used as a technology analysis tool, it can assess the strengths, weaknesses, opportunities and threats associated with different recycling technologies. These four factors of a SWOT analysis can be divided into internal and external factors, where the first two are internal and the last two are external (Phadermrod et al., 2019). Strengths highlight the positive aspects of the technology that provide a competitive advantage, while weaknesses focus on areas that may limit or compromise the performance of the technology. Opportunities explore the external chances for expansion or increased adoption of the technology, while threats consider the external challenges that could hinder successful implementation. For this project, the SWOT analysis was carried out systematically to assess each technology according to the factors and related questions listed in Table 2.

Table 2: The factors of a SWOT analysis and the related questions for the investigation of each factor.

Factor	Questions
Strengths	What are the strengths and advantages of the recycling technology? What factors affect these strengths?
Weaknesses	What are the weaknesses and limitations of the recycling technology? What factors affect these weaknesses?
Opportunities	What are the opportunities for the recycling technology? How can these opportunities be realised?
Threats	What are the threats to the recycling technology? What challenges can arise and cause problems?

Following the brief literature review to select the recycling method, a more detailed and comprehensive review was carried out. The purpose of this was to identify emerging recycling technologies for the SWOT analysis. Due to the limited research in this area, it was challenging to locate relevant information and identify which technologies were applicable to specific recycling methods. The search criteria focused on identifying technologies capable of achieving polymer level degradation that could be adapted to thermoplastics or polyester. This is because polyester was the material under investigation and led to the application of the SWOT analysis to the two recycling technologies TM and SD.

The SWOT analysis formed the basis for a case study, which was further explored in the subsequent analysis. The aim of the case study was to identify technology alternatives for further analysis, reflecting the different treatment options for the polyester fibre post-consumer textile waste collected in Denmark. The technology alternatives were further used to assess the environmental performance of the technologies through a comparative LCA. The defined technology alternatives are: *Alternative 0: Business as usual (BAU)*, *Alternative 1: Thermomechanical (TM)* and *Alternative 2: Selective dissolution (SD)*. A description of the defined technology alternatives is given in section 3.4.

3.3 Process mapping and flow assessment

As part of the research of the defined technology alternatives, it was essential to understand the practical implementation of the different technological processes. This means mapping the process steps involved in the technologies and understanding how the post-consumer textile waste flows through the system. By mapping the processes and flows, it is possible to investigate the recovery rate and where material losses occur within the system. The mapping process provided the insight to create a simple MFA of how the textiles flow through the technology processes and which processes are involved. The MFA for this study begins with post-consumer textile waste as the input flow into the system. It then follows the progression of the textile waste through the treatment process and ends with the recovered polymers.

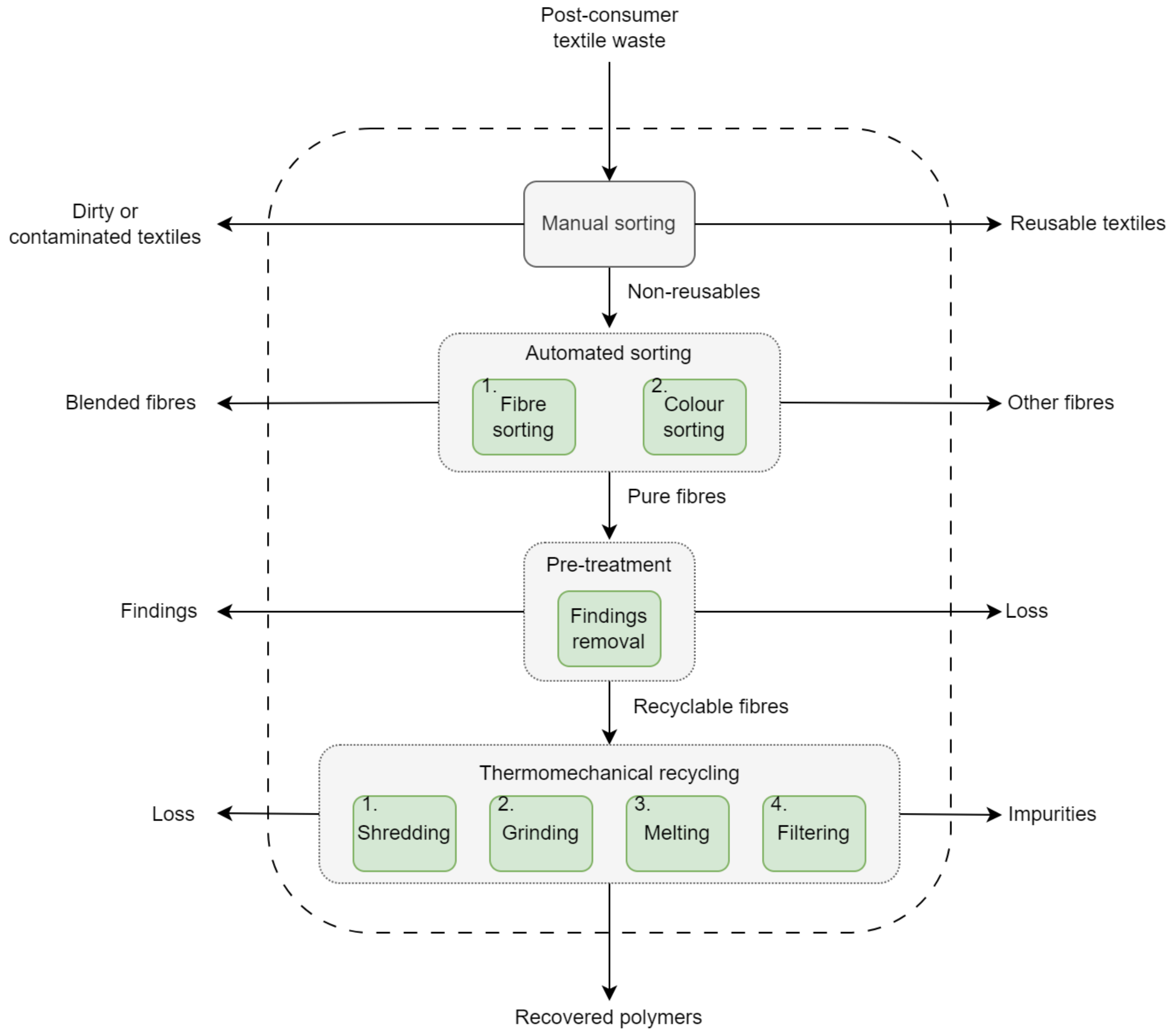

Figure 5: Illustration of the MFA of the TM recycling technology. It includes the processes involved and the material flow through the system. Pure fibres refer to 100% polyester fibres. Blended fibres refer to textiles containing a proportion of polyester fibres. Other fibres refer to textiles containing all fibres other than polyester.

Figure Figure 5 illustrates the processes and material flows involved in TM recycling. This process requires two steps in the automated sorting phase, namely sorting by fibre and by colour. This is to ensure that the textile stream is as pure and clean as possible. As TM recycling cannot remove dyes from textiles, colour sorting is essential. Only the pure polyester fibres are sent for further treatment and subsequent recycling. The TM recycling process itself includes shredding, grinding, melt extrusion and filtering.

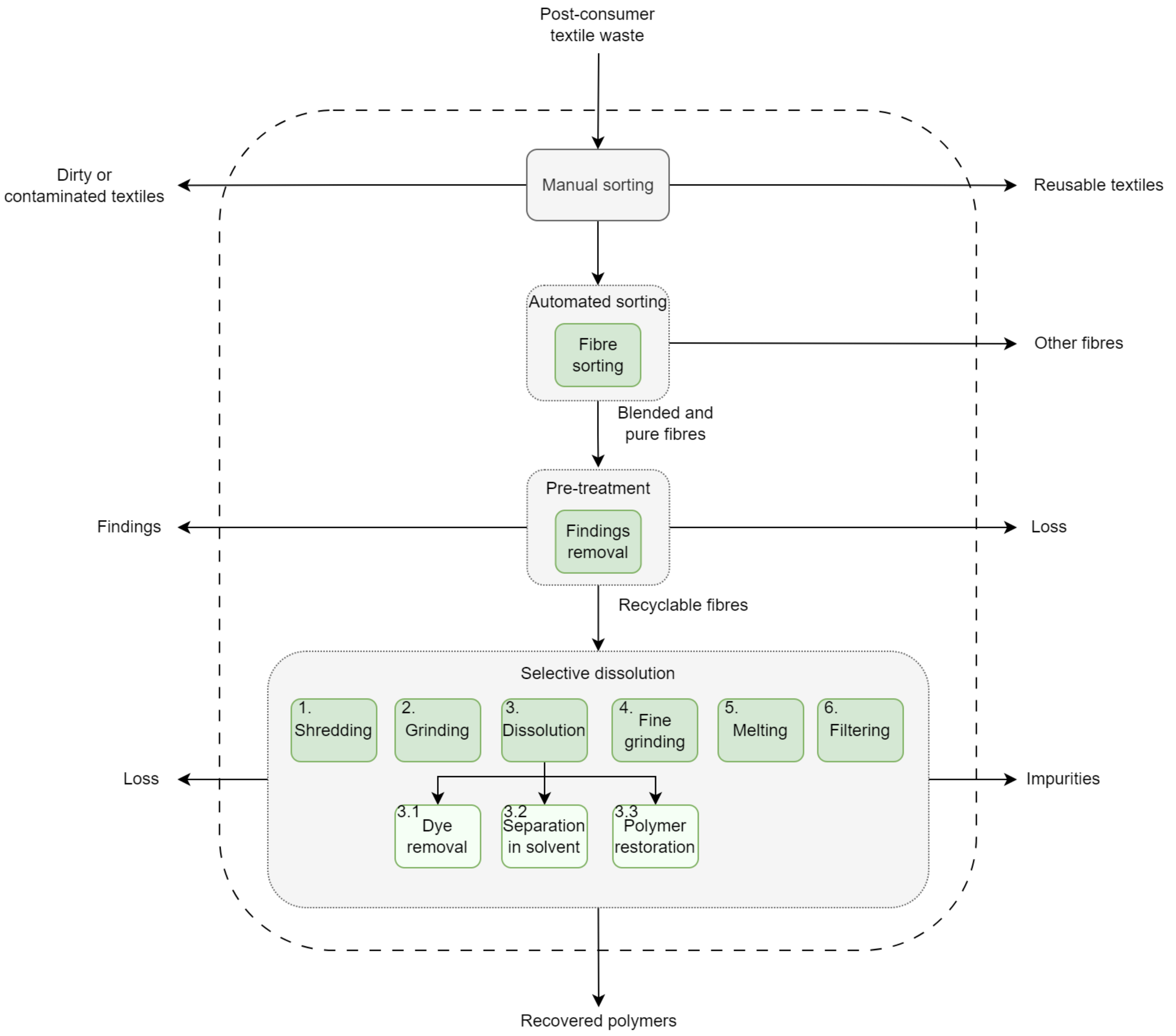

Figure 6: Illustration of the MFA of the SD recycling technology. It includes the processes involved and the material flow through the system. Pure fibres refer to 100% polyester fibres. Blended fibres refer to textiles containing a proportion of polyester fibres. Other fibres refer to textiles containing all fibres other than polyester.

Figure 6 illustrates the processes and material flows involved in SD recycling. Due to SD's ability to remove dyes during the dissolution process, SD requires only one step in the automated sorting phase, which is fibre sorting. Both pure and blended polyester fibres from the sorting stage are then sent for further processing and recycling. These fibres are then further processed using the same steps as for TM recycling, with an exception of the dissolution and fine grinding process.

Even though there are some differences between the processes for the recycling technologies and the flow of textiles through them, it is important to note that the number and nature of these process steps can vary significantly depending on the scale of the operation, from pilot to industrial scale. For example, an initial washing and drying stage at the entry point of the system is ideal to ensure the cleanliness and quality of the textiles before they are processed further. However, this is not normally used at industrial scale and is therefore not included in the process mapping.

3.4 Life cycle assessment

In order to assess the environmental impact of polymer recycling technologies and their treatment of post-consumer textile waste, a LCA will be carried out. This section provides an insight into what an LCA is, what it is used for and how the LCA methodology is used in this study.

LCAs always follow a defined framework and are based on four main phases, namely Goal and Scope definition, Inventory analysis (LCI), Impact assessment (LCIA), and Interpretation (International Organization for Standardization (ISO), 2006). An illustration of this framework is shown in Figure 7.

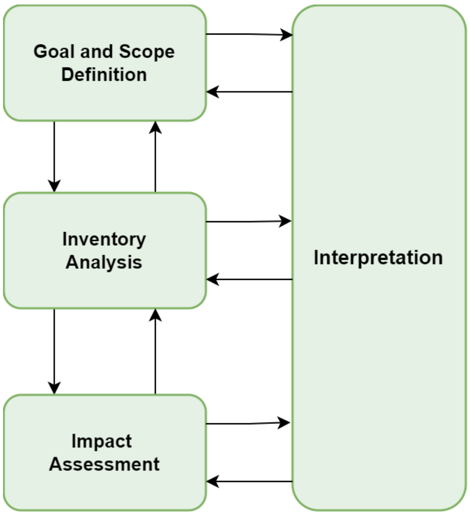

Figure 7: Illustration of the four phases of an LCA framework. Inspired by (International Organization for Standardization (ISO), 2006)

The LCA conducted in this study follows the guidelines and standards presented in the European ISO standards ISO 14040 and ISO 14044 (International Organization for Standardization (ISO), 2006). In addition, the ILCD handbook is used (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010).

The software EASETECH is used to implement the LCA for this study. EASETECH is a software developed at DTU to model LCA for the assessment of environmental technologies. The name is an abbreviation for "Environmental Assessement System for Environmental TECHnologies". EASETECH can carry out complex LCA systems that deal with heterogeneous material flows, in addition to resource use, recovery and emissions associated with environmental management (Clavreul et al., 2014). This study uses EASETECH version 3.6.

3.4.1 Goal and Scope

In this phase the goal of the LCA is defined, followed by defining the Functional unit (FU) and system boundaries for the assessment. The goal of the LCA indicates the intended application and the reasons for conducting the study, as well as the intended audience (International Organization for Standardization (ISO), 2006).

The intended application of the LCA in this study is to evaluate the environmental impacts of identified emerging polymer recycling technologies. It aims to improve the understanding of polymer recycling processes and their potential environmental impacts. The LCA is a simplification of the real world processes, using many assumptions and generalisations. Due to the simplified nature of the LCA performed in this study, it can form the basis for further research in this area. This study and further research may be relevant to stakeholders such as in the textile- and waste management industries, policymakers, and potential decision makers.

Functional unit and reference flow

The FU is the definition of what is being studied. The main purpose of the FU is to provide a reference for the inputs and outputs so that they can be related. If studies have the same FU, they can be easily compared (International Organization for Standardization (ISO), 2006). The following FU and reference flow is the basis for the LCA carried out in this study:

> Functional unit: *The treatment of post-consumer textile waste of polyester fibre type collected annually in Denmark.*
>
> Reference flow: *1 tonne.*

The reference year for this analysis is 2025. This decision is based on data from Logan et al. (2023), which has data on the "Composition of Garments in the 2022 Spring/Summer Danish Pre-Consumer Retail Fast Fashion Market" (Logan et al., 2023). Assuming that these textiles have a lifespan of three years, they are expected to become textile waste by 2025. The geographical focus of the analysis is Denmark. The input flow of post-consumer textile waste into the system is defined according to the definitions of post-consumer textile waste defined in Table 1. This definition include textiles such as clothes, curtains, and towels (Miljøministeriet, 2021).

The purpose of specifying the fibre type in the FU is to focus the analysis on the recycling of this particular fibre. Although the input flow to the system includes various fibre types, this study will focus specifically on the flow of polyester. The reference flow entering the system is normalised to ensure accuracy relative to the system boundaries and in accordance with the FU. To ensure consistency with the flow of polyester fibres, the normalised reference flow of post-consumer textile waste entering the system is set to 1,101 tonnes.

System boundaries

The system boundary in a LCA defines which processes are included in the analysis. The results of the LCA depend on these boundaries. The choice of system boundaries is primarily influenced by the goal and scope of the study and its intended application (International Organization for Standardization (ISO), 2006). The scope of the system does not include the production, sale, use phase, repair, disposal or collection of these textiles. Therefore, the input flow is defined as the total amount of post-consumer textile waste collected and ready for sorting. Furthermore, textiles that are considered to be reusable and are sent to the textile market (e.g. charity organisations or second-hand stores) are not included in the system boundaries. It is assumed that all stages of the process take place in the same place, i.e. transport is not included in the system boundaries. It is assumed that the lost material within the system is sent for energy recovery (incineration) as the system is modelled for Denmark. This means that energy recovery is included within the system boundaries. Below is an illustration and description of the system boundaries for each of the technology alternatives defined for the comparative LCA.

Alternative 0: Business As Usual (BAU)

This alternative is defined based on how post-consumer textile waste is currently treated in Denmark. It is a Business As Usual (BAU) alternative that reflects what happens to post-consumer textile waste if the treatment process remains as it is today. In this treatment alternative, post-consumer textile waste is either incinerated for energy recovery, downcycled into other products of lower quality, or sent for re-use, which is outside the system boundaries. Figure 8 shows the system boundaries for this alternative. An illustration of the system boundaries with quantified flows can be seen in Figure 19 in Appendix B. In addition, and illustration of this alternative modelled in EASETECH can be seen in Figure 22.

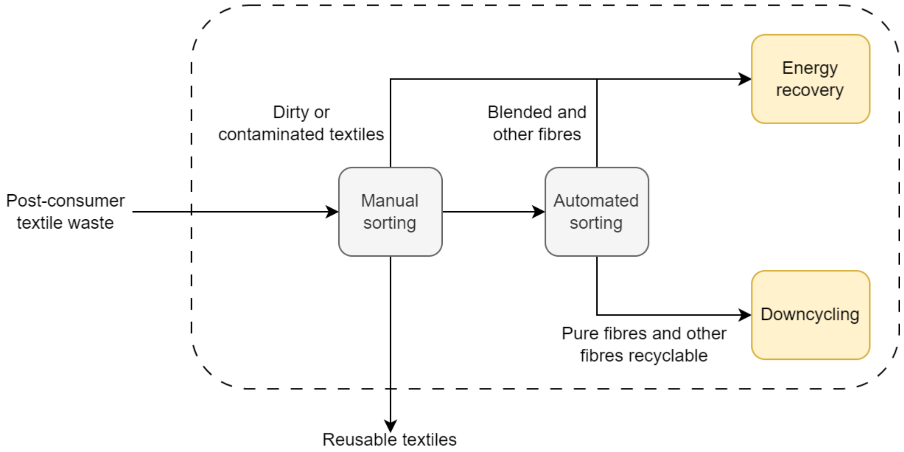

Figure 8: Illustration of the defined system boundaries for technology alternative 0. The yellow processes indicate treatment options other than closed loop recycling.

Alternative 1: Thermomechanical (TM)

This alternative is the TM polymer recycling technology. This alternative reflects the treatment of pure polyester fibres, as this technology can only be applied to pure fibres. The pure fibres are sent for further processing. The the blended and other fibres are sent for downcycling or incineration as in alternative 0. Figure 9 shows the system boundaries for this alternative. An illustration of the system boundaries with quantified flows can be seen in Figure 20 in Appendix B. In addition, and illustration of this alternative modelled in EASETECH can be seen in Figure 23.

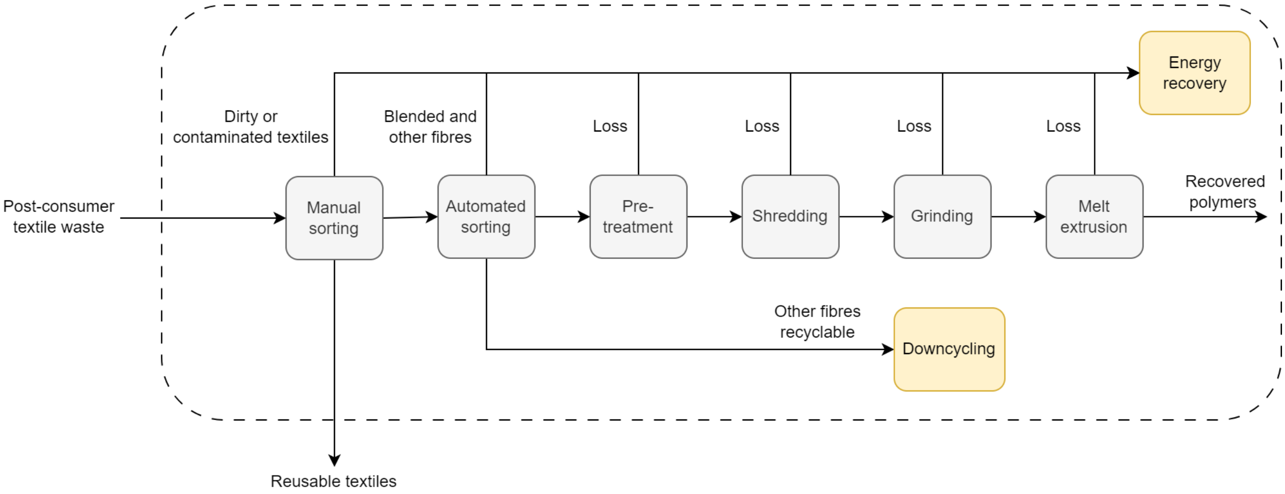

Figure 9: Illustration of the defined system boundaries for technology alternative 1. The yellow processes indicate other treatment options other than the TM recycling process.

Alternative 2: Selective Dissolution (SD)

This alternative is the SD polymer recycling technology, and reflects the treatment of pure and blended polyester fibres. In this alternative, both pure and blended polyester fibres are sent for further processing, while the remaining post-consumer textile waste consists of other fibres, some of which can be downcycled and the rest is sent for incineration as in alternative 0. Figure 10 shows the system boundaries for this alternative. The only difference between the system for alternatives 1 and 2 is the addition of the dissolution and fine grinding processes. An illustration of the system boundaries with quantified flows can be seen in Figure 21 in Appendix B. In addition, and illustration of this alternative modelled in EASETECH can be seen in Figure 24.

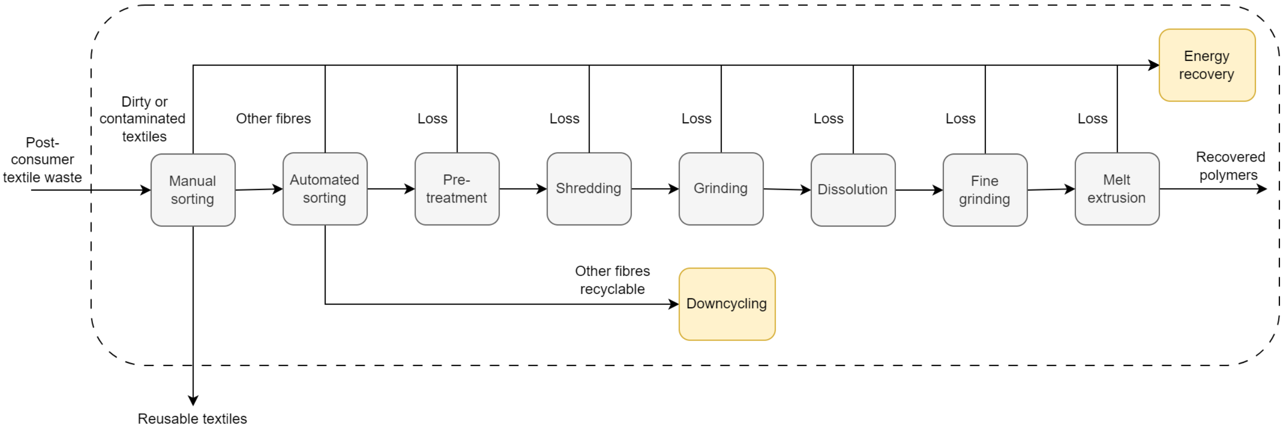

Figure 10: Illustration of the defined system boundaries for technology alternative 2. The yellow processes indicate other treatment options other than the SD recycling process.

The processes included in the system boundaries for the three treatment alternatives are not as detailed as the number of processes included in the process mapping and flow assessment. This is done as a simplification of the systems due to difficulties in finding reliable and detailed data for all the different processes.

3.4.2 Life cycle inventory analysis

A LCI is the second phase of an LCA. This phase involves collecting data and calculating the inputs and outputs of a product system. Data collection identifies uncertainties, data gaps and limitations in the system, which may lead to the need for quantified assumptions, as was the case for this LCA study. Data collection is followed by data calculation, which includes data validation to ensure that the data relate to unit processes and to the FU (International Organization for Standardization (ISO), 2006).

Allocation

Allocation is the distribution of input and output flows of a studied activity among the products within the studied system (International Organization for Standardization (ISO), 2006). Allocation is a method used in the attributional approach to LCA. It converts the multi-product activities into single-product activities. Allocation can be based on different characteristics, which can slightly affect the results. The Ecoinvent database is mostly based on price allocation (economic allocation), with some exceptions such as energy, which is allocated based on exergy (Ecoinvent, 2024). Data from Ecoinvent 3.10, and the system model "Allocation at the point of substitution (APOS)" are used in the LCA of this study. APOS follows an attribution approach where the burden of responsibility is shared between the producers and the users who benefit from the treatment process. To avoid allocation within treatment systems, this system model practices the extension of the product system (Ecoinvent, 2024). This system model is also chosen because this study concerns decision support at the micro-level and the consequence of a decision is therefore of interest (Bjørn et al., 2018). The APOS system model was chosen over both the "allocation, cut-off by classification" and the "substitution, consequential, long-term" models. A brief explanation of why can be found in Appendix B.

Data Collection and assumptions

The data collection for this study is based on the literature found during the process mapping and SWOT analysis and forms the main basis for this LCA. The main literature reviewed included reviews of technologies and alternatives for recycling polyester fibres, studies of different recycling technologies and some LCA studies.

Table 3 shows a description of the specific data to the foreground system and the main data assumptions of this study. All background processes are taken from the Ecoinvent database 3.10 (2023), and an overview of these is given in Table 13 in Appendix B. The parameters used in the LCA model with their respective quantities and sources are shown in Table 12 in Appendix B. The data in this parameter table is expressed per tonne of post-consumer textile waste, while the unit used in Easetech is per kg. This results in all parameters (except the fractions) being divided by 1000 in the modelling.

Table 3: Summary of the LCI data and their main assumptions.

Data	**Source**	**Assumption**	**Process**
Condition of post-consumer textiles	Manual sorting	Same percentage share of non-reusable and contaminated and dirty textiles as previous master thesis.	(Rossi, 2023)
Polyester composition post-consumer textiles	Automated sorting	Fraction of polyester fibres. Based on the number of textiles with 91-100% (pure fibres) and 21-100% (blended fibres) polyester composition and ≤ 10 findings per garment.	(Logan et al., 2023)
Post-consumer textiles for downcycling	Automated sorting	Fraction of downcycled textiles.	(Sandin and Peters, 2018)
Energy and heat requirements	Manual sorting	Similar to Siptex manual sorting.	(Lidfeldt et al., 2022)
Energy and heat requirements	Automated sorting	Similar to Siptex sorting 1 and 2.	(Lidfeldt et al., 2022)
Material loss due to findings removal	Pre-treatment	Average value of Guillotine and picking values from source.	(Rossi, 2023)
Energy requirements	Pre-treatment	-	(Rossi, 2023)
Heat requirements	Pre-treatment, downcycling, shredding, grinding	Based on heating requirements for sorting.	(Lidfeldt et al., 2022)
Material loss	Shredding, grinding	-	(Salim, 2023)
Electricity requirements	Downcycling, shredding, grinding	Similar values to electricity pre-treatment and shredding in source.	(Spathas, 2017)
Material loss	Melt extrusion	Average fraction of loss.	(Tapia-Picazo et al., 2014)
Electricity and heat requirements	Melt extrusion	-	(Gu et al., 2017)
Material recovery	Dissolution	Average fraction of dissolution efficiency.	(Loo et al., 2023)
Used solvent	Dissolution	Similar to the amount of NMMO used for pollycotton separation.	(Loo et al., 2023)
Solvent recovery	Dissolution	Fraction of recovered NMMO solvent.	(Zamani et al., 2015)
Electricity and heat requirements	Dissolution	-	(Zamani et al., 2015)

Substitution

In LCA, resource recovery often involves the use of substitution. This approach credits the environmental benefits of avoiding the impacts associated with the production of new products or materials by replacing them with recovered resources (Vadenbo et al., 2017). Substitution allows the environmental impacts of recycling a product or material to be compared with the impacts of its initial production (Viau et al., 2020). Studies have shown that substitution modelling is a key factor in assessing the environmental effectiveness of a waste management strategy (Viau et al., 2020). This study considers substitution for material and energy recovery, with a substitution ratio of 1:1, i.e. the recovered materials are 100% substitutes for e.g. material or energy. For all technology alternatives, textiles sent for downcycling are considered to substitute the production of lower quality textile products such as carpets and rugs and lower quality fabrics. In addition, textiles sent for incineration are considered to substitute the production of electricity and heat. Alternatives 1 and 2 consider substitution in the recovered polymer process. The materials produced in this process are in the form of polymer granules and these are assumed to substitute the production of 100% virgin PET granules of fossil origin. This assumption of a 1:1 substitution ratio is a very critical assumption for the results and is discussed in relation to the recovery rates in section 4.3.

Additional assumptions

In the EASETECH system, material flows are divided into two specific fractions: “textiles” and “textiles_polyester”. For a material fraction in EASETECH one can see the chemical composition of the specific material fraction is shown as a percentage of the total solids (TS). For the “textiles” fraction, it this is assumed that the EASETECH default settings for the composition of textile materials are adjusted, in particular for biological carbon (Bio C) and fossil carbon (Fossil C). Consequently, this adjustment increases the Fossil C content to 39.1%TS, compared to 13%TS for Bio C, within this defined material fraction. For the “textiles_polyester” fraction, it is assumed that both bio and fossil C are combined, resulting in a material composition that is entirely made up of fossil carbon. The total carbon value for this fraction is therefore 52.1%TS fossil C.

The energy recovery process used in the modelled systems is EASETECH’s standard incineration process. In this process, the same background process of electricity and heat is used as for all other processes, where substitution of electricity and heat is included.

In the dissolution process it is assumed that the used solvent is recovered, although some is lost. This assumption is based on the system being in operation, indicating that the process is already in progress. Consequently, this affects the amount of solvent required in the system, creating a cycle where the used solvent is reused and only the lost fraction is replaced. With regard to the solvent used in the dissolution process, the background processes used for this are general processes where the production process is for a general organic solvent and the market for spent solvent is for a solvent mixture.

Data quality and sensitivity

A perturbation analysis is performed to examine how changes in input parameters affect the overall system and to identify which parameters are most sensitive. This analysis is carried out within the EASETECH software using the same system model as for the LCIA. In this analysis, each parameter is increased by 10%, represented by a default value of 1.1, to assess the model's responsiveness to variations in each parameter. The result of this perturbation analysis is quantified and presented as a sensitivity ratio (SR), which indicates the relative impact of each parameter change on the system. A SR is calculated according to Equation 1 (Clavreul et al., 2012).

$$SR = \frac{\frac{\Delta result}{initial\_results}}{\frac{\Delta parameter}{initial\_parameter}} \tag{1}$$

The SR describes the relative sensitivity of a parameter, which makes it possible to make a comparison between different parameters (Clavreul et al., 2012).

To measure the data quality of the parameters and processes used in this study, the pedigree matrix approach is used. A pedigree matrix assesses the parameters, data and processes according to five independent characteristics, namely Reliability (R), Completeness (C), Temporal Correlation (Tc), Geographic Correlation (Gc) and Further Technological Correlation (FTc), where each of these characteristics is divided into five levels with a score between 1 and 5 (Weidema et al., 2013). The adapted version in this project, including a description of each characteristic, can be found in Table 14 in Appendix B. After each process and parameter is assigned a set of the five indicator scores, a Data Quality Ratio (DQR) is calculated using Equation 2 (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010).

$$DQR = \frac{R + C + Tc + Gc + FTc + X_W \cdot 4}{i + 4} \tag{2}$$

R, C, Tc, Gc and FTc are the assigned scores from 1 to 5 from the pedigree matrix, X_w is the weakest quality level obtained (i.e. highest numerical value) among the data quality characteristics, i is the number of applicable (i.e. not equal to "0") data quality indicators (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010).

3.4.3 Life cycle impact assessment

An LCIA is the third phase of an LCA. This phase defines the impact categories and evaluates the environmental impacts of the modelled system (International Organization for Standardization (ISO), 2006). This is done by using the results from the LCI.

The impact assessment methodology "EF v3.1 no LT" (Environmental Footprint without long term emissions) is used in this study. The method is managed by the European Commission and is a midpoint method that assesses several impact categories. Version 3.1 of this method is also implemented in Ecoinvent (Ecoinvent, 2023). "EF v3.1 no LT" aggregates the inputs and outputs from the LCI into 16 characterised midpoint impact categories, with each impact category having its own unit (Andreasi Bassi et al., 2023). The impact categories included in the "EF v3.1 no LT" with their respective unit and abbreviation used in this study are shown in Table 4.

Table 4: All the impact categories included in the impact assessment method "EF v3.1 no LT" with their unit and abbreviation.

Impact category	**Unit**	**Abbreviation**
Climate change	kg CO2-Eq	CC
Ozone depletion	kg CFC-11-Eq	OD
Human toxicity, cancer	CTUh	HTC
Human toxicity, non-carcinogenic	CTUh	HTNC
Particulate matter	disease incidence	PM
Ionising radiation	kBq U235-Eq	IR
Photochemical ozone formation	kg NMVOC-Eq	POF
Acidification	mol H+-Eq	AC
Eutrophication, terrestrial	mol N-Eq	ET
Eutrophication, freshwater	kg P-Eq	EF
Eutrophication, marine	kg N-Eq	EM
Ecotoxicity freshwater	CTUe	ECF
Land use	dimensionless	LU
Water use	m3 world Eq deprived	WU
Resource use, minerals and metals	kg Sb-Eq	RUMM
Resource use, energy carrier	MJ, net calorific value	RUEC

4 Results and Discussion

This chapter presents the results of the methods used in this study, including the results of the SWOT analysis and the LCA. The results are interpreted and discussed in detail, followed by an assessment of the limitations of the study and recommendations for future research.

4.1 SWOT analysis

This section provides a brief overview of the reason for the chosen recycling method. In addition, the results and findings of the SWOT analysis of the two technologies, TM and SD, are presented and discussed.

4.1.1 Choice of recycling pathway

The decision to focus on the polymer recycling process was motivated by a number of factors. As introduced in section 2.5, polymer recycling is considered to be less established or mature than fibre recycling. It offers clear advantages in terms of output quality. Polymer recycling produces fibres with higher quality characteristics compared to conventional fibre recycling approaches. Although monomer and oligomer recycling technologies have the potential to produce fibres of even higher quality than polymer recycling, they are characterised by more process steps, followed by higher energy and water consumption. Given the desire to explore a less established recycling method, the decision to focus on polymer recycling was made after a brief initial literature review. At that time, polymer recycling appeared to be the most promising and understandable method for investigation.

4.1.2 Thermomechanical

The results of the SWOT analysis of the TM recycling technology are presented with five main points for each of the four factors considered in a SWOT analysis. These results can be seen in Table 5.

The TM recycling technology is characterised by minimal use of chemicals and low water requirements. Water is mainly used in the washing phase of the pre-treatment process, ensuring that the process is not water intensive. This aspect is in line with environmental sustainability goals by reducing resource consumption (Loo et al., 2023). The recycling process mirrors established techniques used in the melt processing of virgin materials, although it differs in certain procedural steps. It is similarly applied to the recycling of solid plastic waste. This familiarity in process design contributes to the efficiency and cost-effectiveness of the technology and facilitates easy implementation (European Commission et al., 2021). In addition, if the input textile waste is sufficiently clean, this technology can produce high quality fibres comparable to those from virgin sources. The cost of this recycling process remains competitive with that of virgin polyester production, offering significant opportunities for up-scaling (Ellen MacArthur Foundation, 2017).

Although TM recycling has some strengths, there are certain weaknesses associated with the technology. TM recycling of polymers is known to cause degradation due to the combined effects of mechanical shear and heat during melt processing. This degradation occurs repeatedly in each recycling cycle and negatively affects the polymers and fibres (Loo et al., 2023; European Commission et al., 2021). Various properties of the recycled material are affected by these changes. Specifically, there are changes in thermal properties such as crystallisation and melting

Table 5: Results of the SWOT analysis of the TM recycling technology. The table shows the five main elements of each factor considered.

Factor	Main elements
Strengths	Minimal chemical and water use Similar to melt processing of virgin materials Efficiency and cost-effectiveness High quality output
Weaknesses	Polymer Degradation Changed material properties Energy intensive Colour dyes and contamination issues Require clean input
Opportunities	Governmental policies Dominance of thermoplastic fibres Technological advancement Consumer awareness Sustainability
Threats	Polymer degradation Feedstock quality requirements Competition and cost Shift to sustainable textiles Market risks

temperatures, mechanical properties including reduced fibre length, and physical properties affecting colour and surface characteristics. These changes consequently affect the quality of the recovered material (Loo et al., 2023).

In addition, TM recycling is energy intensive and requires high temperatures, which further contributes to its environmental impact (Loo et al., 2023). Furthermore, the process does not remove pigments and dyes, which makes knowing the exact composition of the material critical. An accurate understanding of the colour, type and level of contamination of the textile, together with effective sorting and separation of the input materials, is critical for optimising the recycling process (Loo et al., 2023). To ensure a high quality output, the recycling process requires input materials that are as uncontaminated as possible. Effective segregation and sorting are crucial and require detailed information on contaminant levels, fibre types and overall composition (European Commission et al., 2021).

Despite its weaknesses, TM recycling offers promising opportunities. Political pressure and new regulations for the treatment and disposal of textile waste are significantly increasing the market opportunities for this recycling technology. This trend is further supported by increasing consumer awareness, which is driving demand for the recovery of valuable materials from used textiles. In addition, as thermoplastic fibres dominate the textile market, and TM recycling is very similar to the processing and production of virgin materials, there is a strong incentive to adopt this technology (Phan et al., 2023).

However, there are several challenges that could hinder the adoption and implementation of this technology. The process is susceptible to polymer degradation during processing, which may have a negative impact on the willingness to establish and use such recycling facilities. In addition, the need for high quality feedstock and the sensitivity to textiles containing mixed fibres pose significant investment risks. Competition from other recycling technologies and the costs associated with establishing efficient sorting, pre-treatment and recycling facilities are also significant threats. In addition, increased consumer awareness and a market shift towards more sustainable textiles, such as natural or plant-based fibres, could reduce the demand for recycling technologies that primarily treat synthetic and man-made fibres.

4.1.3 Selective dissolution

The results of the SWOT analysis of the SD recycling technology are presented with five main points for each of the four factors considered in a SWOT analysis. These results can be seen in Table 6.

Table 6: Results of the SWOT analysis of the SD recycling technology. The table shows the five main elements of each factor considered.

Factor	Main elements
Strengths	Versatility Contaminant removal Efficient output recovery High quality output Polymer restoration capability
Weaknesses	Importance of input quality High cost and requirements Environmental impact Additional processing stages Adoption barriers
Opportunities	Governmental policies Consumer awareness High yields Versatility in processing Investment attractiveness
Threats	Market risks Resource efficiency Competitive disadvantage High Cost Price competition

SD is a versatile technology that can process a wide range of textile fibres, including blended materials such as polycotton, as well as pure polyester fibres. It is also effective in treating textiles containing additional materials such as elastane or nylon (European Commission et al., 2021; Loo et al., 2023). This technology is particularly good at removing contaminants, including dyes and small amounts of elastane, thereby purifying the input material (European Commission et al., 2021). The SD process produces different outputs. For example, dissolving polycotton produces both polymer granules and cellulosic pulp. The polymer granules can be recycled, while the cellulose pulp can be processed into regenerated cellulose. Both outputs can be transformed into new yarns for textile products, demonstrating the efficiency of the process in terms of resource recovery (European Commission et al., 2021). The choice of solvents for the SD of polyester in a polycotton textile would not significantly degrade the cellulose (Loo et al., 2023).

A key advantage of SD is its ability to separate and purify recycled materials, resulting in a colourless, pure polymer of a quality comparable to virgin materials. This feature is important if the recovered fibres are to replace virgin production (European Commission et al., 2021). Additionally, for degraded polymers, and contaminated or very damaged fibres, this technology is almost the only option to restore the polymers (European Commission et al., 2021).

Despite the strengths of SD, there are still some weaknesses associated with this technology. One of these is that effective sorting and a thorough understanding of the composition of the textile input stream are critical to achieving efficient processing. Although not as critical as in TM recycling, these factors play an important role in achieving the desired output quality and quantity in SD processes (European Commission et al., 2021). Another weakness is that the cost of SD is higher than that of TM recycling and is closer to the cost of virgin material production. This technology also requires additional purification steps if the input material is highly contaminated, which further increases the costs (European Commission et al., 2021).

Additionally, SD requires chemicals such as additives and solvents, resulting in a higher environmental impact compared to other recycling technologies. This aspect is a significant weakness that could label the technology as environmentally unfriendly (European Commission et al., 2021). While SD is effective in treating textiles with blended fibres, such as polycotton, which consists of a few fibre types, it faces challenges with blends containing many fibre types. This makes textiles with many types of fibres less preferred, mainly due to economic factors and limited market availability of third materials (European Commission et al., 2021). Furthermore, the presence of contaminants in the input material can affect the efficiency of the recycling process, although a certain level of contamination is manageable (Loo et al., 2023).

The use of chemical-based recycling technologies such as SD is less widespread than other methods such as TM recycling. This limited use is often attributed to the higher skill requirements, processing costs and initial investment required. In addition, this technology consumes significant amounts of chemicals, energy and water. This may further hinder its adoption (Loo et al., 2023).

Despite the strengths and weaknesses of this recycling technology, it offers several promising opportunities for further development and application. Similar to TM recycling, SD will benefit significantly from increasing political pressure and new regulations for the treatment and disposal of textile waste. These changes are expected to create significant market opportunities for this technology. In addition, growing consumer awareness of sustainable practices is likely to drive demand for technologies that can recover valuable materials from used textiles.

SD offers a technological advantage by potentially offering higher yields compared to TM recycling (European Commission et al., 2021). This advantage positions SD as a compelling option for adoption, although it does not have the same technological advancement as TM recycling, which is a technology similar to existing technology for virgin fibre production. An additional strength of SD is its ability to process a variety of textile fibres and different blends (Loo et al., 2023). This versatility allows it to address a wider segment of textile waste, potentially encouraging more significant investment in this technology. The ability to handle different textile inputs is critical to extending its application to more waste streams, thereby increasing its overall impact on textile waste reduction.

However, this technology is not without its threats. SD faces significant market risks similar to those faced by TM recycling. A prevailing trend in textile production towards the use of predominantly pure fibres may reduce the attractiveness of SD. This technology tends to be less favourable compared to other recycling methods that use less energy, water and chemicals. As a result, SD may become less competitive in markets that prioritise cost efficiency and resource conservation (Loo et al., 2023). The competitiveness of SD is also threatened by other recycling technologies that have not only lower operating costs but also potentially lower investment costs. These factors contribute to a challenging environment for implementation and investment in SD. The high initial investment and operating costs associated with this technology limit its widespread adoption and use (Loo et al., 2023).

As there are high costs associated with the implementation and establishment of SD facilities, another significant threat is price competition from virgin fibres, which are often cheaper than recycled alternatives. This cost differential is a barrier to the wider acceptance and integration of recycled fibres produced by SD, especially in cost-sensitive markets (Loo et al., 2023).

4.1.4 Comparison of thermomechanical and selective dissolution

The SWOT analysis provided valuable insights into both the TM and SD technology. Even though they share some similarities in terms of requirements of high-quality input material and the capability to process high quality outputs, they differ significantly in their strengths and weaknesses. The TM technology is characterised by minimal chemical and water use, efficiency, cost effectiveness and process similarity to melt processing of virgin materials. However, it suffers from polymer degradation, sensitivity to colourants and contaminants, and high energy consumption. On the other hand, SD technology is characterised by its versatility, effective removal of contaminants and dyes, and efficient recovery of output. Its main drawbacks are its high cost and intensive use of energy, water and chemicals, which increase its environmental impact.

Both TM and SD recycling technologies are critically dependent on clean feedstock. Detailed knowledge of the fibre types and compositions in the textile inputs is essential to optimise these processes and achieve high quality outputs. The importance of the sorting process is highlighted by the diversity of fibre blends in the textile market, which pose significant recycling challenges (Harmsen et al., 2021). As a result of the importance of a clean feedstock for both technologies, clothing waste from fashion or household sources is often considered unsuitable for recycling. This is due to the high risk of contamination, posing significant challenges to achieving efficient recycling results (European Commission et al., 2021).

Despite the differences and similarities between the technologies, it is important to identify which factors are considered most important for this study. The SWOT analysis focuses not only on internal factors - strengths and weaknesses - which indicate areas under the direct control and potential for improvement of stakeholders such as companies in the textile recycling industry, but also on external factors - opportunities and threats - which represent elements beyond their control. While the primary objective of this study is to identify and compare emerging polymer recycling technologies, assessing their performance, advantages and disadvantages, it is clear that strengths and weaknesses are the most important factors to consider. However, a comprehensive strategic plan must consider all elements of the SWOT analysis, particularly in preparation for the implementation of these technologies in the textile recycling industry.

4.2 Results and interpretation

This section presents the results of the LCIA in addition to the results from the data quality and sensitivity analysis. All the results are interpreted.

4.2.1 Impact assessment results

The LCIA for three different technology alternatives were modelled using the method described in section 3.4.3. The results of the LCIA were presented with the impacts of each category for each of the processes involved in the systems. To make the tables and graphs in this section easier to understand, abbreviations are used for the impact categories. These can be found in Table 4. The overall results from the impact assessment for all processes and all the different impact categories for each alternative can be found in Appendix D in Table 15, Table 16, Table 17 for the BAU, TM and SD alternatives respectively.

For the three treatment alternatives, the total impact across all processes can be seen in Table 7. For all the alternatives and all impact categories, the overall environmental impact of the whole system is negative. The exception is the Climate Change (CC) impact category for the BAU alternative, where the overall impact is positive, i.e. a burden.

Table 7: Results of environmental impact across all processes for each impact category in the three treatment alternatives. Red-coloured boxes indicate high impact, green-coloured boxes indicate low impact, and the other colours represent varying degrees of impact in between.

Impact category	**BAU**	**TM**	**SD**	**Unit**
CC	7.82E+01	-3.34E+02	-3.42E+02	kg CO2-Eq
OD	-7.22E-06	-2.05E-03	-3.53E-03	kg CFC-11-Eq
HTC	-1.26E-06	-2.91E-06	-3.34E-06	CTUh
HTNC	-8.61E-06	-1.36E-05	-1.37E-05	CTUh
PM	-6.44E-05	-8.91E-05	-6.90E-05	disease incidence
IR	-2.20E+01	-3.20E+01	-3.15E+01	kBq U235-Eq
POF	-2.37E+00	-4.35E+00	-4.51E+00	kg NMVOC-Eq
AC	-5.73E+00	-8.04E+00	-6.74E+00	mol H+-Eq
ET	-7.10E+00	-1.08E+01	-9.61E+00	mol N-Eq
EF	-4.51E-02	-6.32E-02	-5.64E-02	kg P-Eq
EM	-5.86E-01	-9.20E-01	-8.67E-01	kg N-Eq
ECF	-1.96E+03	-4.09E+03	-1.04E+03	CTUe
LU	-8.86E+03	-1.05E+04	-7.91E+03	-
WU	-2.54E+02	-3.92E+02	-3.71E+02	m3 world Eq deprived
RUMM	-1.19E-03	-5.70E-03	-8.67E-03	kg Sb-Eq
RUEC	-9.00E+03	-1.99E+04	-2.23E+04	MJ, net calorific value

A number of impact categories were selected to illustrate the environmental impacts of the three modelled systems. These impact categories were chosen because some of the categories had significantly higher overall impacts than others and are central to addressing the impacts of textiles and textile waste. The chosen impact categories are Climate Change (CC), expressed in kg $CO_2 - eq$, Ecotoxicity Freshwater (ECF), expressed in $CTUe$, Land Use (LU), which is dimensionless, Water Use (WU), expressed in $m^3 world - Eq - deprived$, and Resource Use, Energy Carrier (RUEC), expressed in *MJ, net calorific value*.

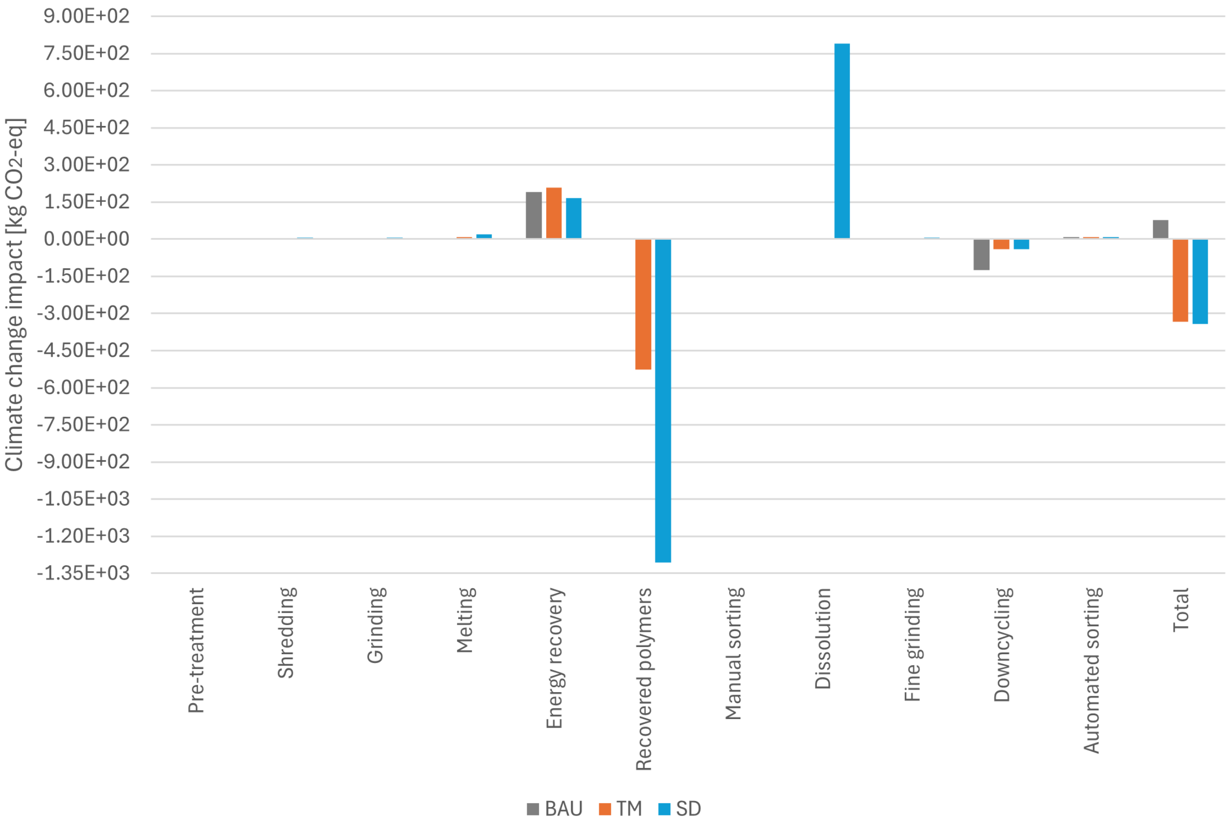

Figure 11: Climate change (CC) impact of the three treatment alternatives given in kg $CO_2 - eq$ per tonne of textile waste treated. The grey, orange and blue colours on the lines show the impacts of BAU, TM and SD respectively.

For the CC impact category, the total impact of all processes is negative for TM and SD, while the impact of BAU is positive. This means that the TM and SD treatment alternatives for polyester textile waste are better than the BAU treatment alternative when considering the emissions from all processes associated with the treatment alternatives. The CC impacts from the three treatment alternatives can be seen in Figure 11.

In the ECF impact category, all processes show a net negative impact, with TM recycling being the better alternative. Specifically, TM recycling has the lowest environmental impact, followed by the BAU method and then the SD alternative. This suggests that, in terms of freshwater ecotoxicity, the existing treatment method is more effective than SD for processing polyester textile waste, but TM recycling is the most environmentally beneficial option. The ECF impacts from the three treatment alternatives can be seen in Figure 12.

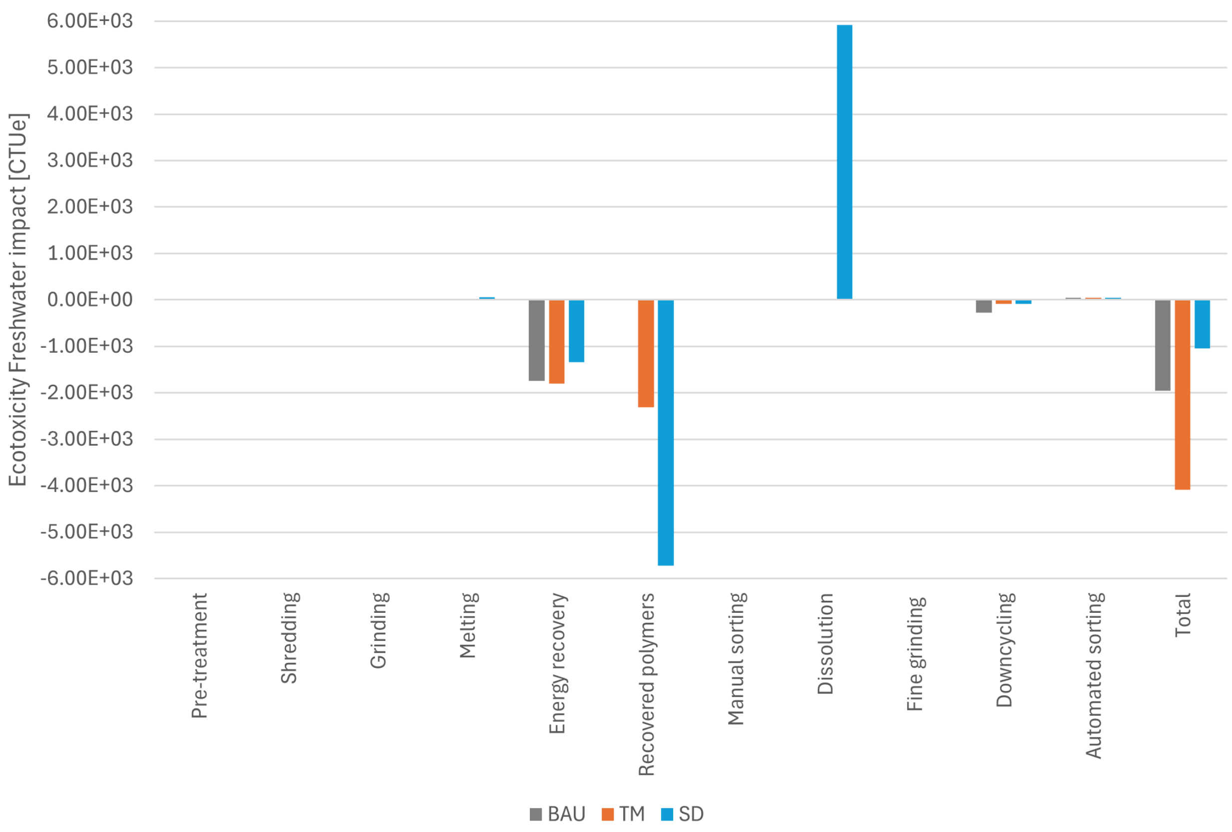

Figure 12: Ecotoxicity freshwater (ECF) impact of the three treatment alternatives given in $CTUe$ per tonne of textile waste treated. The grey, orange and blue colours on the lines show the impacts of BAU, TM and SD respectively.

For the impact category LU, the total impact of all processes is negative. The distribution of the total impacts for the different alternatives is similar to the distribution for the impact category ECF but with even lower impacts for this category. This implies that in terms of land use, it is better to treat polyester textile waste with the TM alternative, followed by the BAU and SD alternatives, but overall the total impact of all alternatives will have a negative impact on land use. The LU impacts from the three treatment alternatives can be seen in Figure 13.

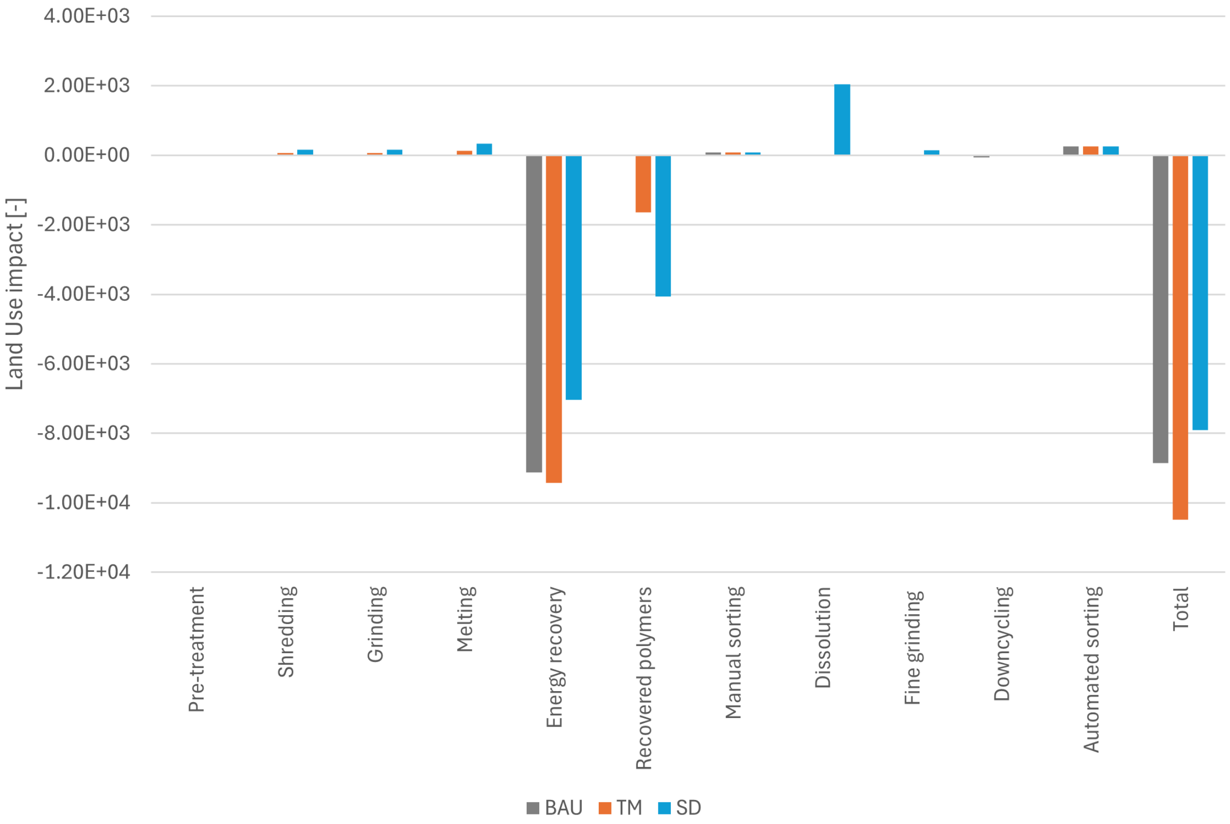

Figure 13: Land Use (LU) impact of the three treatment alternatives per tonne of textile waste treated. The grey, orange and blue colours on the lines show the impacts of BAU, TM and SD respectively.

For the impact category WU, the total impact of all processes is also negative, but not as much as for LU. Again, the TM recycling alternative is the alternative with the lowest impact, but the SD alternative has an almost comparable total impact. The overall results for this impact category suggest that there is less impact associated with water use when choosing the TM or SD recycling alternative before BAU. The WU impacts from the three treatment alternatives can be seen in Figure 14.

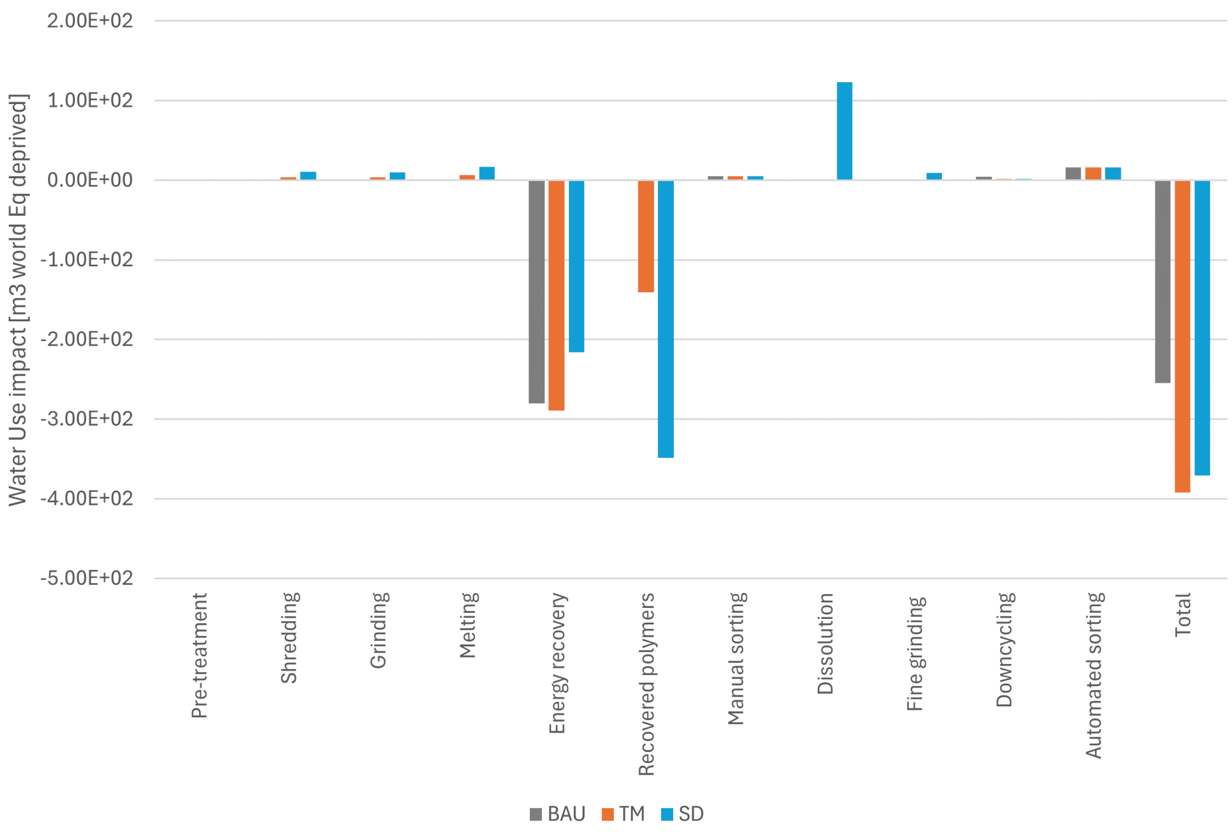

Figure 14: Water Use (WU) impact of the three treatment alternatives given in $m^3 world - Eq - deprived$ per tonne of textile waste treated. The grey, orange and blue colours on the lines show the impacts of BAU, TM and SD respectively.

In the RUEC impact category, which assesses the use and extraction of energy resources from the earth, the total impact of all processes is also negative. Within this category, the SD alternative has the most negative total impact, closely followed by the TM alternative. These results are consistent with those for the WU impact category, indicating that both the TM and SD alternatives consume fewer energy resources than the BAU alternative. The specific impacts of the three treatment alternatives within the RUEC category are shown in Figure 15.

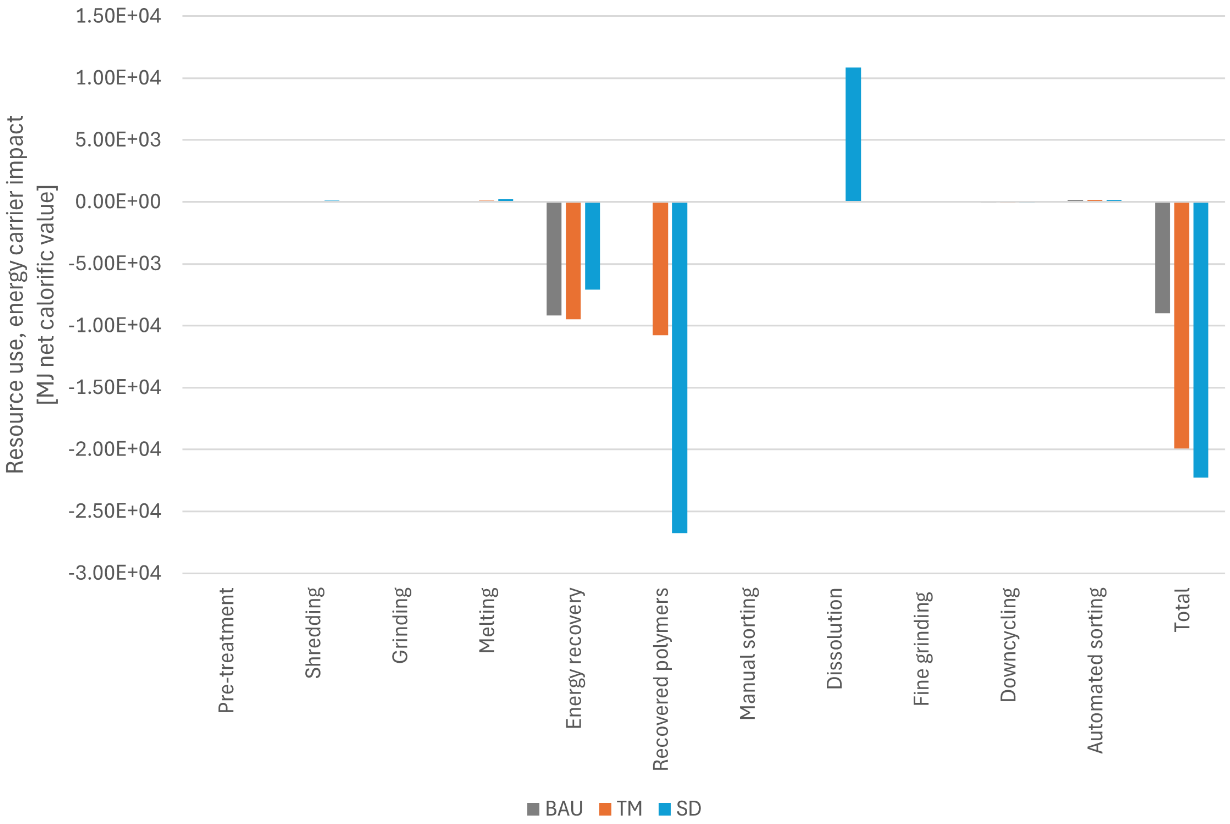

Figure 15: Resource use, energy carrier (RUEC) impact of the three treatment alternatives given in *MJ, net calorific value* per tonne of textile waste treated. The grey, orange and blue colours on the lines show the impacts of BAU, TM and SD respectively.

For better comparison of the different impact categories, the LCIA results are normalised in EASETECH. The results of the normalised impacts for BAU can be seen in Table 8. The normalised results for the TM and SD alternatives can be seen in Appendix D in Table 18 and Table 19 respectively. The normalised results are expressed in Personal Equivalents (PE) and allow the impact categories to be compared. The impact category with the most negative impact is the RUEC for all three treatment alternatives.

Table 8: Results of normalised impact for processes in the BAU alternative expressed in Personal Equivalence (PE). Red coloured boxes indicate high impact, green coloured boxes indicate low impact, and the other colours represent varying degrees of impact in between. The second last column of the matrix shows the total normalised impact across all processes.

Impact category	**Automated sorting**	**Energy recovery**	**Manual sorting**	**Down-cycling**	**Total**	**Unit**
CC	1.15E-03	2.54E-02	3.78E-04	-1.65E-02	1.04E-02	kg CO2-Eq
OD	3.24E-06	-1.42E-04	1.06E-06	8.93E-08	-1.38E-04	kg CFC-11-Eq
HTC	2.09E-03	-7.37E-02	6.83E-04	-2.18E-03	-7.31E-02	CTUh
HTNC	1.09E-03	-6.15E-02	3.59E-04	-6.70E-03	-6.68E-02	CTUh
PM	4.82E-04	-1.08E-01	1.63E-04	-7.58E-04	-1.08E-01	disease incidence
IR	3.39E-04	-5.79E-03	1.10E-04	1.26E-04	-5.21E-03	kBq U235-Eq
POF	6.19E-04	-5.07E-02	2.05E-04	-8.01E-03	-5.79E-02	kg NMVOC-Eq
AC	6.92E-04	-1.01E-01	2.31E-04	-2.94E-03	-1.03E-01	mol H+-Eq
ET	5.92E-04	-3.55E-02	1.95E-04	-5.35E-03	-4.01E-02	mol N-Eq
EF	3.98E-04	-2.87E-02	1.31E-04	1.30E-04	-2.80E-02	kg P-Eq
EM	3.91E-04	-2.57E-02	1.29E-04	-4.93E-03	-3.01E-02	kg N-Eq
ECF	7.14E-04	-3.07E-02	2.34E-04	-4.84E-03	-3.46E-02	CTUe
LU	3.05E-04	-1.11E-02	9.97E-05	-7.78E-05	-1.08E-02	dimensionless
WU	1.39E-03	-2.43E-02	4.52E-04	3.88E-04	-2.21E-02	m3 world Eq deprived
RUMM	1.21E-03	-2.06E-02	3.95E-04	3.05E-04	-1.87E-02	kg Sb-Eq
RUEC	2.16E-03	-1.41E-01	7.08E-04	-1.45E-05	-1.38E-01	MJ, net calorific value

4.2.2 Data quality and sensitivity results

In this section, the results of the data quality analysis and the sensitivity analysis are presented separately, followed by the combined results of the two analysis.

Data quality

Using the pedigree matrix approach presented in Appendix C,in combination with the DQR presented in section 3.4.2, the quality of the parameters and foreground processes in the modelled systems can be assessed. The DQR values for these parameters and processes are detailed in Table 26 and Table 27 in Appendix E. Based on the DQR results, the data quality is classified into three levels: “high quality”, “basic quality” and “data estimate”. These classifications are based on the rankings outlined in Table 28 in Appendix E, adapted from ILCD Handbook (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010). Parameters and processes categorised under the lowest quality level can be found in Table 9.

Table 9: Data quality ratios for parameters and foreground processes with a quality level defined as “Data estimate”” according to the .

	DQR
Parameters	
contaminated_dirty	3.11
other_fibres_rec	3.33
loss_findings	3.11
loss_melting	3.33
recovered_fibres_dissolution	3.00
solvent	3.22
solvent_recovery	3.89
electricity_downcycling	3.33
electricity_fine_grinding	3.33
electricity_grinding	3.33
electricity_shredding	3.33
Processes	
Dissolution	3.17
Shredding	3.48
Grinding	3.48
Fine grinding	3.48

Sensitivity analysis

The perturbation analysis was performed as described in section 3.4.2 and indicates how sensitive the overall results of the LCA are to a change in the parameters. By performing this sensitivity analysis it was possible to identify of the most sensitive parameters in each alternative. The most sensitive parameters for each treatment alternative in five selected impact categories can be seen in Table 10. The sensitivity for all parameters and all impact categories for the BAU, TM and SD alternatives, can be seen in Appendix E in Table 20, Table 21 and Table 22, respectively.

Table 10: Overview of the most sensitive parameters in the three modelled alternatives presented for five impact categories. Red coloured boxes indicate high sensitivity in terms of positive impact, green coloured boxes indicate high sensitivity in terms of negative impacts, and the other colours represent varying degrees of sensitivity in between.

Parameter	**CC**	**ECF**	**LU**	**WU**	**RUEC**
Unit	kg CO2-Eq	CTUe	-	m3 world Eq deprived	MJ, net calorific value
BAU					
contaminated_dirty	4.87E-01	1.38E-01	1.61E-01	1.72E-01	1.59E-01
non_reusables	4.77E-01	8.68E-01	8.49E-01	8.49E-01	8.46E-01
other_fibres_rec	-7.54E-01	-4.42E-02	-1.02E-01	-1.17E-01	-1.03E-01
TM					
contaminated_dirty	-1.14E-01	6.63E-02	1.36E-01	1.11E-01	7.19E-02
non_reusables	1.12E+00	9.37E-01	8.72E-01	9.02E-01	9.30E-01
other_fibres_rec	1.76E-01	-2.12E-02	-8.60E-02	-7.59E-02	-4.66E-02
SD					
non_reusables	1.12E+00	7.52E-01	8.30E-01	8.96E-01	9.38E-01
recovered_fibres_dissolution	4.15E+00	4.68E+00	-5.58E-02	5.38E-01	1.00E+00
solvent	-1.92E+00	-5.47E+00	-1.33E-01	-3.12E-01	-4.28E-01
solvent_recovery	9.41E+01	2.68E+02	6.51E+00	1.53E+01	2.10E+01

To improve the validation of the parameters sensitivity and its impact on model results, sensitivity scores can be normalised. Normalisation allows the sensitivity of each parameter to be compared with the most sensitive parameter within each impact category, providing a clearer understanding of how each parameter is weighted against each others in terms of sensitivity. The normalised sensitivity results for BAU, TM and SD are presented in Table 23, Table 24 and Table 25 in Appendix E.

In addition, these normalised sensitivity results, combined with the DQR for each parameter, are used to identify key parameters in the modelled systems. Key parameters are those with both high sensitivity and low data quality, indicating areas where improvements in data quality could have a significant impact on model results. The plot of DQR vs. sensitivity for the CC impact category for BAU, TM and SD, are shown in Figure 16, Figure 17 and Figure 18, respectively. In addition, illustrations of the key parameters for the three treatment alternatives for the ECF and LU impact categories can be found in Appendix E.

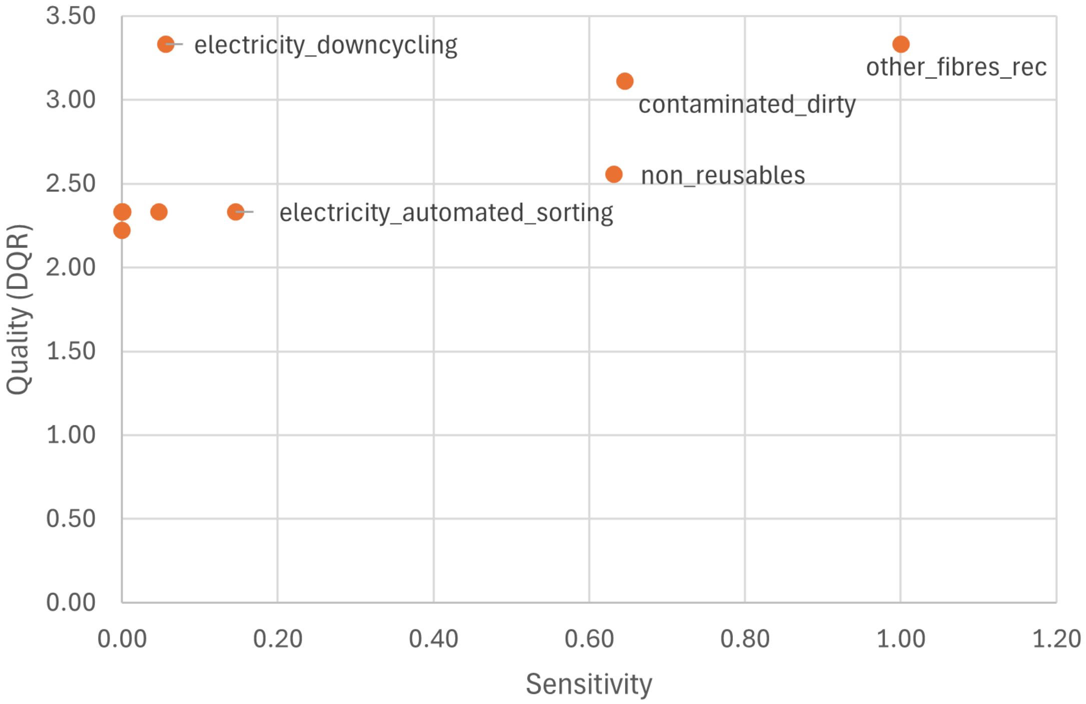

Figure 16: Plot of DQR vs. sensitivity of parameters affecting climate change in the BAU alternative. Parameters appearing in the top right-hand corner are identified as key parameters for the impact on Climate change (CC).

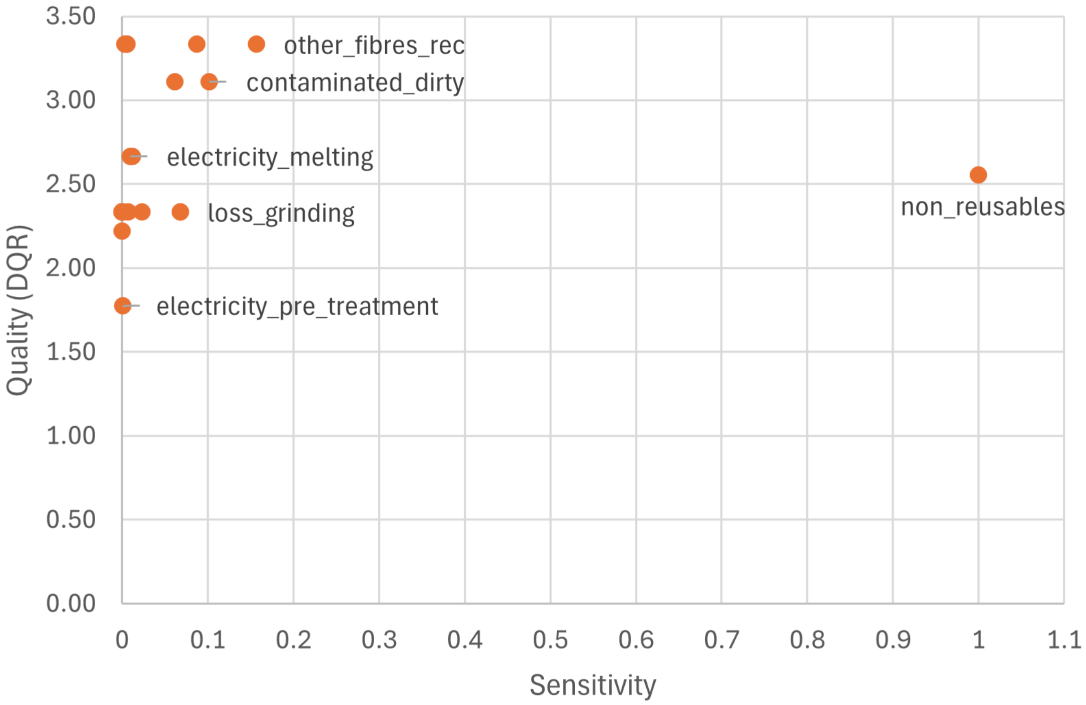

Figure 17: Plot of DQR vs. sensitivity of parameters affecting climate change in the TM alternative. Parameters appearing in the top right-hand corner are identified as key parameters for the impact on Climate change (CC).

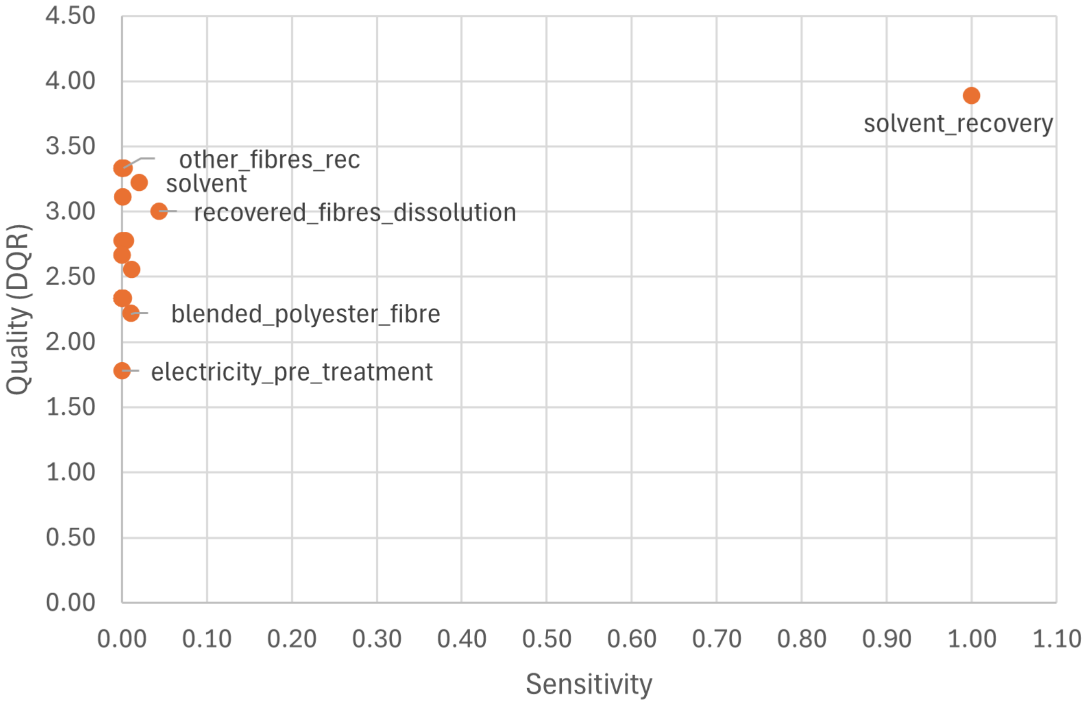

Figure 18: Plot of DQR vs. sensitivity of parameters affecting climate change in the SD alternative. Parameters appearing in the top right-hand corner are identified as key parameters for the impact on Climate change (CC).

4.3 Discussion

This section interprets and discusses the results of the previous sections. It begins with an interpretation and discussion of the results of the sensitivity and data quality analysis, followed by an examination of the results of the impact assessment and an assessment of the critical assumptions made for this study.

4.3.1 Sensitivity and data quality

Table 10 indicate that the sensitivity analysis showed different degrees of parameter sensitivity for the different impact categories. For the BAU and TM recycling alternatives, the parameters affecting the CC impact category showed the highest sensitivity, while for the SD alternative, the LU impact category was the most sensitive. Non-reusable textile waste, which is the largest material fraction by mass in all alternatives, has a significant impact on all five impact categories. In particular, in the CC category, the processing of textile waste leads to increased greenhouse gas emissions, which has a positive impact on this category.

The total mass entering the system is identified as the most sensitive parameter across all treatment alternatives. This is expected as the input flow is typically critical to the overall sensitivity of the system and is therefore not included as one of the most sensitive parameters in table Table 10. From Table 10 one can see that for the BAU and TM alternatives, the parameters that determine the amount of textile waste sent for further processing, such as the *contaminated_dirty* and *non_reusable*, show a high sensitivity. Furthermore, the amount of textile waste defined as *other_fibres_rec*, which containing non-polyester fibres that are sent for downcycling, also shows significant sensitivity. This can be explained by the large mass flows controlled by these parameters.

For the CC impact category, sending a higher volume of non-polyester fibres for downcycling, coupled with background processes, results in negative impacts for the BAU alternative, but positive impacts for both the TM and SD alternatives.

Form Table 10 one can see that in the SD alternative, the critical parameters affecting all impact categories are solvent recovery, the solvent itself and the fibres recovered from the dissolution process. The importance of solvent use and recovery is particularly pronounced in the CC impact category, where solvent recovery shows an exceptionally high sensitivity. In fact, the highest of all parameters. This is closely followed by the sensitivity associated with fibre recovery from dissolution. The prominence of these parameters highlights the key role of the dissolution process within the system. Changes in this process could lead to significant shifts in the results, underlining its significant influence on the overall environmental impact.

The DQR uses a pedigree approach that assesses data quality based on several critical indicators: reliability, completeness, temporal correlation, geographical correlation and technological correlation. Together, these indicators determine the trustworthiness of the data underlying the parameters and processes within the model. The DQR scores provide an indication of the quality of the data and processes used in the model. In Table 9, approximately one third of all parameters in the three modelled systems are identified as being of the lowest quality level. Similarly, almost half of the processes in the foreground system are classified as low quality. The significant proportion of data and processes rated as low quality raises concerns about the overall reliability and credibility of the model's results.

The combination of parameter sensitivity and data quality allows the identification of key parameters within the systems. Key parameters are those that are both highly sensitive and have low data quality, as indicated by a high DQR score. The identification of these key parameters is crucial as it highlights the data that should be updated or improved as a priority. As different impact categories may have different key parameters, the focus on which parameters require attention may shift depending on the specific impact category being analysed.

Figure 16 show that in the context of climate change, within the BAU treatment alternative, the most sensitive parameters are also those with the lowest data quality and are therefore classified as key parameters. This designation underlines their importance in the modelled alternative. Similarly, there are notable differences between the TM and SD treatment alternatives as seen in Figure 17 and Figure 18. In the TM alternative, the key parameter is the amount of non-recyclable textile waste, reflecting its critical role in the impact of the system. In the SD alternative, the solvent recovery rate emerges as the key parameter due to its low data quality and high sensitivity, highlighting its key influence on the environmental performance of the system.

4.3.2 Impact assessment

Table 7 show that overall, for all the five chosen impact categories, the total impact across all processes is negative, with an exception of the CC impact from the BAU alternative. On the other hand, the plots of the impact in the five impact categories, show that the recovered polymers process in the SD alternative, turn out to have a significantly negative impact for all the chosen impact categories. The impact from the recovered polymer process in the TM alternative is also always negative, but not as ”impact saving” as the SD alternative. This could be due to the differences in the recovery rate for the two alternatives, where the SD have a higher recovery rate and thereby can substitute more virgin polyester production than the TM alternative can.

When assessing the environmental impacts associated with the energy recovery process across all treatment alternatives, all selected impact categories show a negative impact, with the exception of CC Figure 11. This is probably because energy recovery or incineration reduces the amount of waste sent to landfill, which is considered the least desirable option in the waste hierarchy. Reducing the amount of waste sent to landfill not only reduces the amount of land required for waste disposal, but also helps to prevent the leaching of toxic substances into groundwater, thereby protecting freshwater resources. These factors contribute to the negative impacts observed in the ECF and LU categories seen in Figure 12 and Figure 13. In addition, Figure 14 show that the WU impact category shows minimal impacts from energy recovery and incineration, as these processes require significantly less water compared to other steps in the textile waste recycling process. The positive impact of energy recovery in the CC impact category, seen in Figure 11, is likely due to the fact that incineration directly emits greenhouse gases into the atmosphere. The incinerated material is predominantly polyester fibres, which contain fossil-based carbon. Incineration of these fibres adds additional carbon to the atmosphere. This may also explain why the SD alternative has a lower energy recovery impact than TM recycling. In the SD process, the textile stream contains a mixture of polyester and other types of fibres, with the latter being the ones that are primarily incinerated.

The RUEC impact category illustrated in Figure 15, shows potentially lower impacts compared to the other impact categories. This could be due to the system models the recycling of polyester fibres derived from oil - a major resource and energy source containing fossil carbon. Recycling these oil-based materials can save significant energy by reducing the need for virgin materials derived from oil. This reduction in the use of virgin materials not only helps to reduce environmental impact, but also reduces the depletion of oil, a non-renewable energy source. Consequently, the recycling process helps to conserve critical resources by offsetting the need for new oil extraction.

When looking at key processes that contribute to the overall impact within the selected impact categories, automated sorting is a notable process. The automated sorting process is identified as a positive contributor to all selected impact categories due to its energy intensive nature. In particular, this process consumes significant amounts of electricity and heat to perform its functions. While automated sorting alone has a significant resource demand, its positive impacts are somewhat mitigated by the negative impacts of other processes within the system. As a result, the overall environmental impact of the system is not unduly influenced by the contributions of automated sorting. The automated sorting process not only contributes to an increase in the environmental impact in all impact categories. However, it also plays a crucial role in improving the overall efficiency of the recycling system. By using more energy-efficient equipment and advanced sorting machines, this process can handle a greater volume of textiles while using less energy. The complexity of the textiles and the need for detailed, thorough sorting add to the energy requirements of this process, underlining the importance of sophisticated technology in managing different fibre types and compositions.

One of the processes that always has a positive impact for all selected impact categories is the dissolution process. This is only a process in the SD alternative, which can explain why, for example, the BAU alternative has a lower impact than the SD alternative in some of the impact categories. Dissolution involves more assumptions and uncertainties than other processes. It is unique in that it involves the use of solvents. It is assumed that the process is fully operational, excluding any independent solvent production. The included solvent production only compensates for operational losses, with an estimated 98% solvent recovery rate, leaving only 2% additional solvent to be produced based on process requirements. Ideally, dedicated solvent production and solvent treatment processes should be established. The inclusion of these processes could significantly alter the results of the analysis, but they are not included due to insufficient data on their consumption requirements.

In addition, solvent consumption is a critical factor in this study; it is assumed that 19 kg of solvent is required per kg of textile waste treated. Given such high solvent consumption, scaling up operations to treat more than one tonne of textile waste would lead to a significant increase in solvent consumption, increasing the environmental and operational impacts. This assumption is based on data indicating the amount of NMMO solvent required to process polycotton and to extract cellulose from polyester fibres. However, the feedstock for SD recycling does not only consist of polycotton blends, which casts doubt on the applicability of this amount of solvent to other fibre types and blends.

Furthermore, the solvent production process considered in this study uses a generic organic solvent, which may not accurately represent the specific impacts of the solvent used in SD processes. Similarly, the treatment of used solvent is assumed to be a market for spent solvent mixtures, not tailored to the specific solvent used, which could further affect the accuracy of the results.

4.3.3 Critical assumptions

In this section, the assumptions that are considered to be critical for the results of the impact assessment are described and discussed.

Transport

In this study it is assumed that all stages of the process take place within a single factory at the same location, eliminating the need to consider transport. Typically, each stage of textile production takes place in different locations, sometimes in different countries, requiring extensive logistics and transport (Niinimäki et al., 2020). This is also likely to be the case for recycling processes, including those modelled in this study.

As the focus of this study is on a comparative LCA of different recycling technology alternatives, the omission of transport impacts may not significantly affect the relative assessment of one technology over another. However, it's important to note that including transport would likely increase the environmental impacts associated with both SD and TM recycling. This increase in environmental impact due to transport, which may be more significant for SD recycling due to the number of process steps required, could critically influence decision making by highlighting the increased overall impact. Ultimately, taking into account emissions from transport between different processing steps and facilities would show a significantly higher environmental impact for both recycling methods. Recognising these increased impacts is crucial for decision makers when assessing and comparing the sustainability of different recycling technology alternatives.

In addition, many of the processes sourced from Ecoinvent are based on data from Denmark or Europe. This geographical focus could influence the results and the overall environmental assessment of the recycling alternatives. The assumption that all activities take place locally in Denmark or Europe could be misleading, as much of the production of PET polymers and chemicals typically takes place outside Europe.

Material composition

The composition of polyester fibres in the input stream is derived from 2022 data on the Danish pre-consumer fashion market (Logan et al., 2023), focusing specifically on textiles containing polyester. The calculation of the polyester content in the incoming textile waste is based on two criteria: the amount of pure fibres is determined from textiles containing 91-100% polyester, and the amount of mixed fibres is determined from textiles containing 21-100% polyester. Both categories follow a filtering criterion that excludes garments with more than 10 findings or those containing less than 21% polyester.

In the SD treatment alternative, both pure and blended polyester fibres are further processed using solvent-based dissolution. However, the output from the dissolution process destined for melt extrusion still contains other non-polyester fibres that are part of the blended materials. This composition is important because the dissolving process should dissolve the non-polyester fibres, leaving only the polyester fibres for further treatment. This assumption has important implications for the LCIA, potentially leading to inaccuracies in the calculated amount of recovered material and its subsequent substitution in the polymer recovery process. Such errors could have a significant impact on the overall results of the LCIA.

Substitution rate

Typically, substitution is used in LCAs to quantify the ability of recovered energy and recycled materials to avoid primary production and its associated impacts and emissions (Viau et al., 2020). The substitution rate is an important aspect of this study, which assumes a 1:1 ratio between energy recovery, downcycling and the recovered polymer process. This means that the recovered material or energy directly replaces the production of new material or energy. Specifically, in the recovered polymer process, recovered polymer granules from textile waste are assumed to replace virgin polymer granules. However, this assumes that the recycled and virgin materials are of similar quality, which is unlikely to be the case.

The main difference lies in the nature of the substitutable products; recovered polymers may not be of the same quality as virgin polymers (Viau et al., 2020). Energy recovery assumes perfect substitution, where 1 kWh of recovered energy is equivalent to 1 kWh from the grid. However, for recovered polymers, the process may result in losses, meaning that, for example, the recovered material from one T-shirt may not be sufficient to produce another T-shirt of similar quality. Despite this, studies, including those reviewed in (Viau et al., 2020), generally assume a 1:1 substitution rate for textiles, on the basis that recovered textiles are of equivalent quality to what they replace. This assumption has implications for the discussion of recovery rates within recycling schemes.

The recovery rate, defined as the proportion of waste material successfully recovered relative to the total waste generated, is influenced by system performance and process losses. The analysis shows that the recovery rates for the TM and SD alternatives are 13.53% and 33.54% respectively, demonstrating that the SD alternative achieves a significantly higher rate due to the greater amount of polyester fibres processed. Specifically, the TM alternative processes only 18.2% of post-consumer textile waste. The SD alternative processes an additional 30.4%, giving a total of 48.6% of post-consumer textile waste.

With a 1:1 substitution rate and assuming the same quality, the TM and SD alternatives would replace 13.53 and 33.54 kg of virgin polymer granulate production, respectively. This substitution is plausible as polymer recycling can produce materials of similar quality to virgin materials (Damayanti et al., 2021). However, the calculated recovery rates indicate that an input of one tonne of textiles does not yield one tonne of recovered material. One reason for this is that the input material contains fibres other than the target fibre, which are not further processed in the recycling process. This weakens the assumption of a 1:1 substitution.

To extend the concept of substitution, it's important to note that the recovered polymers are only modelled to replace the production of virgin PET polymers. However, the model does not specify the end use of these polymers. Although the input is post-consumer textile waste, there's no certainty that the recovered PET polymer will be used to make new textile fibres. Ideally, in a closed-loop recycling scenario, the recovered PET would actually be converted back into new fibres. This distinction highlights a potential gap between the theoretical substitution model and the practical application of recovered materials.

4.4 Limitations of the study and future research

Although this study provides some insightful results and enhances the understanding of emerging polymer recycling technologies, it has significant limitations. A key challenge is the under-researched nature of polymer and textile recycling, which limits access to primary data. This lack of data necessitates reliance on assumptions and estimates, which affects the reliability and applicability of the results for decision making. While some data are of high quality - geographically relevant, recent and reliable - data completeness remains a challenge. For example, the data on non-reusable textiles destined for further processing comes from a single Master's thesis, which represents the practice of only one organisation. This introduces uncertainties due to potential variations between different organisations and actors sorting textile waste.

Further challenges are posed by the early stage of development of polymer recycling technologies. These technologies have not yet been scaled up and are still in the development phase, leading to a lack of detailed knowledge about process specifics and resource consumption. This gap has necessitated assumptions and simplifications of system processes and reliance on poor quality data or estimates for key processes such as sorting, dissolving, shredding and grinding.

A critical assumption affecting the validity of the study is the 1:1 substitution ratio, which assumes that recovered polymers are of the same quality as virgin polymers and can fully substitute the production of new virgin polymers. This optimistic assumption is likely to bias the environmental impact assessment of the technologies modelled, suggesting lower impacts than might be realistic with a more conservative substitution ratio.

The complexity and diversity of the textile waste stream further complicate this study. Textiles consist of different fibre types and material compositions, making the separation and sorting processes essential for effective recycling particularly challenging. This heterogeneity not only complicates the recycling process, but also affects data quality, where an in-depth understanding of material composition is essential for efficient recycling and the generation of trustworthy results.

Despite its limitations, this study provides valuable insights into emerging polymer recycling technologies and their operation. To improve the understanding of the performance of these technologies, as well as their advantages and disadvantages, future research should prioritise improving data quality and re-evaluating the substitution ratio assumption. These are identified as critical areas where greater focus could significantly refine the findings of the study.

The research highlighted that approximately one third of the parameters used were of low quality, which affects the overall reliability of the study's findings. Therefore, a primary goal for future research should be to improve the quality and reliability of these parameters. In addition, many of the low quality parameters were also found to be highly sensitive, meaning that even small changes in these parameters could dramatically alter the results. These key parameters - both low quality and high sensitivity - should be the focus of future research to improve data reliability.

Another critical area for further investigation is the substitution ratio. The assumption of a 1:1 substitution ratio in this study significantly influences the results. Future research could explore different scenarios with different substitution ratios to see how these adjustments affect the results. Such an analysis would provide deeper insights into the impact of substitution ratios on the system and underline the importance of this assumption in modelling realistic recycling scenarios. Exploring different substitution rates would not only refine the results, but also help to understand the wider implications of recycling practices.

5 Conclusion

This study was initiated to explore how polymer recycling could serve as an effective textile waste management solution, and and to address existing knowledge gaps, challenges and opportunities in this area. The primary objective of this study was to investigate a particular method of textile recycling, focusing on emerging technologies and comparing these with existing treatment options. Through an in-depth investigation, this research has provided valuable insights into the possibilities of polymer recycling methods and the performance of the two specific technologies TM and SD.

This research uncovered opportunities driven by the high production rates of textile fibres and the shift towards a circular economy model that emphasises reduction, reuse and recycling. This transition will increase the viability of recycling solutions for textile waste management. However, this study also identified significant gaps, in particular the complexity of textile materials, the under-researched nature of polymer recycling and issues with accurate substitution rates. These gaps not only highlight the challenges of recycling textile waste, but also underline the broader issues within the industry.

A SWOT analysis assessed the strengths, weaknesses, opportunities and threats associated with the TM and SD technologies. This analysis, combined with process mapping and flow assessment, helped to identify critical processes and trace material flows within the systems. To further assess their performance and environmental impact, an LCA was carried out using EASETECH. This combined approach has provided a detailed understanding of the capabilities and environmental impacts of these emerging recycling technologies.

The SWOT analysis provided valuable insights into the two recycling technologies studied. The process mapping and flow assessment showed that both TM and SD technologies have many similar process steps and material flows. However, they differ significantly in their strengths and weaknesses. TM is efficient and cost-effective, but struggles with polymer degradation and energy consumption; SD is good at removing contaminants and efficiently recovering output, but is hindered by high operating costs and significant environmental impacts.

Despite these differences, both technologies are good at producing high quality outputs, but require clean or high quality inputs to be effective. While TM technology is particularly susceptible to input contamination, SD technology is less susceptible and is also capable of producing even higher quality outputs. These results highlight the different advantages and disadvantages of each technology.

The LCA carried out in this study showed significant differences between the TM and SD recycling technologies. Both technologies showed a reduction in emissions and climate change impacts compared to the BAU treatment option and provided environmental savings in most impact categories. The LCA identified specific processes within the recycling operations that significantly influence these impacts. For example, the dissolution process in the SD technology resulted in positive emissions in all impact categories, highlighting its critical role in determining the environmental performance of the SD approach. Conversely, the polymer recovery process consistently produced negative impacts for both technologies, illustrating its effectiveness in replacing virgin polymer materials. This was particularly evident under the 1:1 substitution assumption, where all recovered materials were considered to fully replace their virgin counterparts, thereby reducing the overall environmental impact. Beyond climate change, the RUEC category also emerged as a key area where both technologies achieved significant impact reductions.

Although the LCA highlighted the environmental benefits of the TM and SD recycling technologies, the sensitivity and data quality analysis introduced some uncertainty into the results. Many critical parameters showed high sensitivity and a significant amount of data was of low quality, which affect the reliability of the results. Further research is needed to reduce these uncertainties and improve the reliability of the results. Despite these uncertainties, the study confirms that both TM and SD technologies are viable options for the management of textile waste.

However, it's important to note that the core problem of textile waste management is the overproduction of fibres and textiles. Recycling technologies alone cannot solve the problem of increasing textile waste; a fundamental shift from the traditional linear economic model of take, make and waste to a more sustainable circular model of reduce, reuse and recycle is essential. This study concludes that while polymer recycling technologies offer effective solutions for the treatment of textile waste, they should be part of a broader strategy to move towards circular economy practices. In addition, the results of this study should be interpreted with caution and further research is needed to obtain more accurate and reliable results.

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A Background material

Table 11: Overview of the definition, maturity, advantages and disadvantages of possible closed-loop recycling methods.

Recycling method	Definition	Maturity	Advantages and Disadvantages
Fabric	Reuse fabric from a complete textile product or a garment to make new textile products.[1] Can also be referred to as material reuse or remanufacturing.[2]	Inconsistent supply of fabric makes large-scale production of fabric recycling limited. The fabric is often too small to be reused, or the quality of the fabric is too low.[2]	Does not require advanced technology. But is labour-intensive as it requires extensive collection and sorting processes, making its applicability somewhat limited.[2]
Fibre	Breaks down the fabric, but the original fibres are retained.[1] It is often referred to as mechanical recycling, as the fabric is mechanically shredded.[2]	It is the most widely used recycling method in the textile recycling industry, but is still at an early stage of development.[3]	Shredding reduces fibre length and leaves contaminants and dyes in the shredded material, reducing fibre quality.[2] Production of new yarns requires the addition of higher quality fibres. [4]
Polymer	Breaks down both the fabric and the fibres, but retains the polymers, which are the chemical structure of the material. [2] The recycling process can be a combination of mechanical, thermal and chemical processes.	Rapidly evolving recycling method, but still in the early stages of development. Development and research of the technologies are in progress. [2]	Produces material similar to virgin material but degrades polymer chains with repeated fibre recovery. The quality of the recycled polymer depends on the quality of the input material.[4]
Oligomer	Breaks down fabrics, fibres and partial degradation of polymers to obtain oligomers.[5] The recycling process can be a combination of mechanical, thermal and chemical processes.	Similar to polymer recycling.	Similar to polymer recycling.
Monomer	Breaks down fabrics, fibres and polymers into individual monomers, the original building blocks of polymers. [2] The recycling process can be a combination of mechanical, thermal and chemical processes.	Similar to polymer recycling	Great potential for creating high quality material, resulting in fibres of similar quality and properties to virgin fibres. [4]

[1] (Sandin and Peters, 2018) [2] (Ellen MacArthur Foundation, 2017) [3] (European Commission et al., 2021)
[4] (Damayanti et al., 2021) [5] (Grigore, 2017)

B LCA material

Choice of system model

The ”cut-off by classification” model assumes that recyclable products have no environmental impacts and assigns responsibility for any impacts to the producer, with initial production costs only applied to the first user. This model excludes impacts from the extraction and initial production of raw materials. On the other hand, the APOS model was also preferred to the ”substitution, consequential, long-term” model because of its effectiveness in reducing the overall impact of the system by substituting standard supply chain inputs with by-products, thereby minimising negative impacts (Ecoinvent, 2024).

Quantified systems

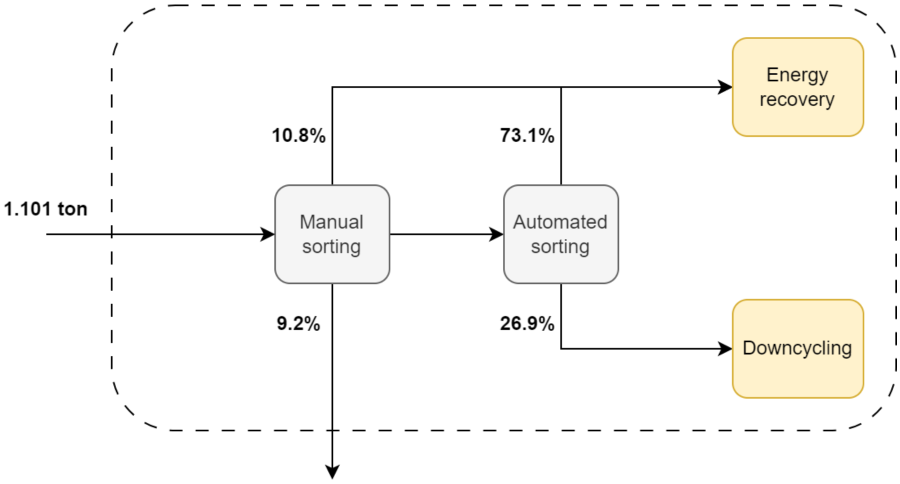

Figure 19: Illustration of the defined system boundaries for treatment alternative 0 with quantified flows.

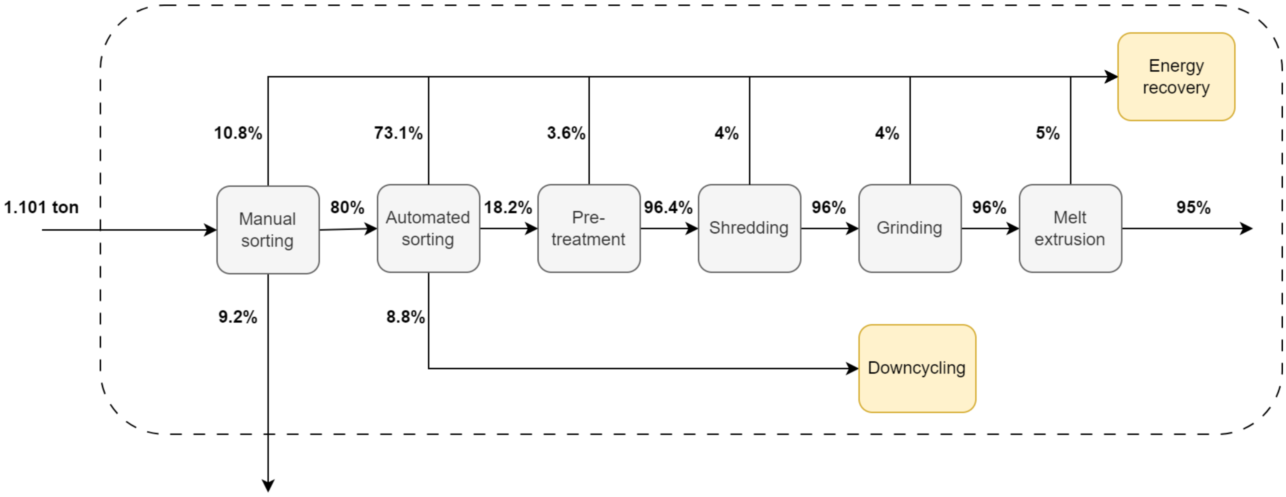

Figure 20: Illustration of the defined system boundaries for treatment alternative 1 with quantified flows

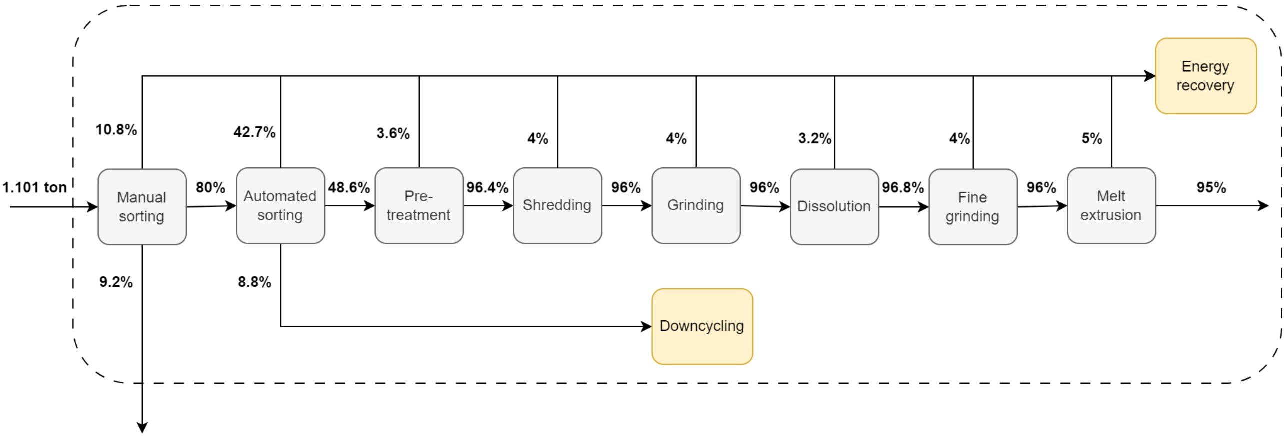

Figure 21: Illustration of the defined system boundaries for treatment alternative 2 with quantified flows

Table 12: Overview of the parameters and corresponding amounts used in the LCA analysis. The amount of electricity and heat is given per tonne of textile waste treated. The amount of solvent is given per kg of textile waste treated.

Parameter	**Amount**	**Unit**	**Source**
Manual sorting			
contaminated_dirty	10.8	%	(Rossi, 2023)
non_reusables	80	%	(Rossi, 2023)
electricity_manual_sorting	16.9	kWh	(Lidfeldt et al., 2022)
heat_manual_sorting	0.7	MJ	(Lidfeldt et al., 2022)
Automated sorting			
pure_polyester_fibre	18.2	%	(Logan et al., 2023)
blended_polyester_fibre	30.4	%	(Logan et al., 2023)
other_fibres_rec	8.75	%	(Sandin and Peters, 2018)
electricity_automated_sorting	64.97	kWh	(Lidfeldt et al., 2022)
heat_automated_sorting	0.4	MJ	(Lidfeldt et al., 2022)
Pre-treatment			
loss_findings	3.6	%	(Rossi, 2023)
electricity_pre_treatment	6.806	kWh	(Rossi, 2023)
heat_pre_treatment	0.2	MJ	(Lidfeldt et al., 2022)
Shredding			
loss_shredding	4	%	(Salim, 2023)
electricity_shredding	92.593	kWh	(Spathas, 2017)
heat_shredding	0.2	MJ	(Lidfeldt et al., 2022)
Grinding			
loss_grinding	4	%	(Salim, 2023)
electricity_grinding	92.593	kWh	(Spathas, 2017)
heat_grinding	0.2	MJ	(Lidfeldt et al., 2022)
Dissolution			
recovered_fibres_dissolution	96.8	%	(Loo et al., 2023)
solvent_recovery	98	%	(Zamani et al., 2015)
solvent	19	kg	(Loo et al., 2023)
electricity_dissolution_process	1.111	kWh	(Zamani et al., 2015)
heat_dissolution_process	5000.0	MJ	(Zamani et al., 2015)
Fine grinding			
loss_fine_grinding	4	%	(Salim, 2023)
electricity_fine_grinding	92.593	kWh	(Spathas, 2017)
heat_fine_grinding	0.2	MJ	(Lidfeldt et al., 2022)
Melt extrusion			
loss_melting	5	%	(Tapia-Picazo et al., 2014)
electricity_melting	165.0	kWh	(Gu et al., 2017)
heat_melting	432.0	MJ	(Gu et al., 2017)
Downcycling			
electricity_downcycling	92.593	kWh	(Spathas, 2017)
heat_downcycling	0.2	MJ	(Lidfeldt et al., 2022)

Table 13: Baground processes form Ecoinvent and corresponding amounts used in the LCA analysis.

Activity name	**Reference**	**Amount**	**Unit**	**Geography**	**Sector**	**Activity type**
Dissolution						
solvent production, organic	solvent, organic	solvent*(1-solvent_recovery)	kg	GLO Global	Chemicals	Transforming activity
market for spent solvent mixture	spent solvent mixture	solvent*(1-solvent_recovery)	kg	Europe without Switzerland	Waste treatment	Market activity
Downcycling						
fibre and fabric waste, polyester to generic market for waste polyethylene terephthalate	fibre and fabric waste, polyester	-1	kg	GLO Global	Waste treatment	Transforming activity
Recovered polymers						
market for polyethylene terephthalate, granulate, amorphous	polyethylene terephthalate, granulate, amorphous	-1	kg	GLO Global	Chemicals	Market activity
All processes						
market for electricity, medium voltage	electricity, medium voltage	-	kWh	DK Denmark	Electricity	Market activity
market for heat, district or industrial, other than natural gas	heat, district or industrial, other than natural gas	-	MJ	Europe without Switzerland	Heat	Market activity

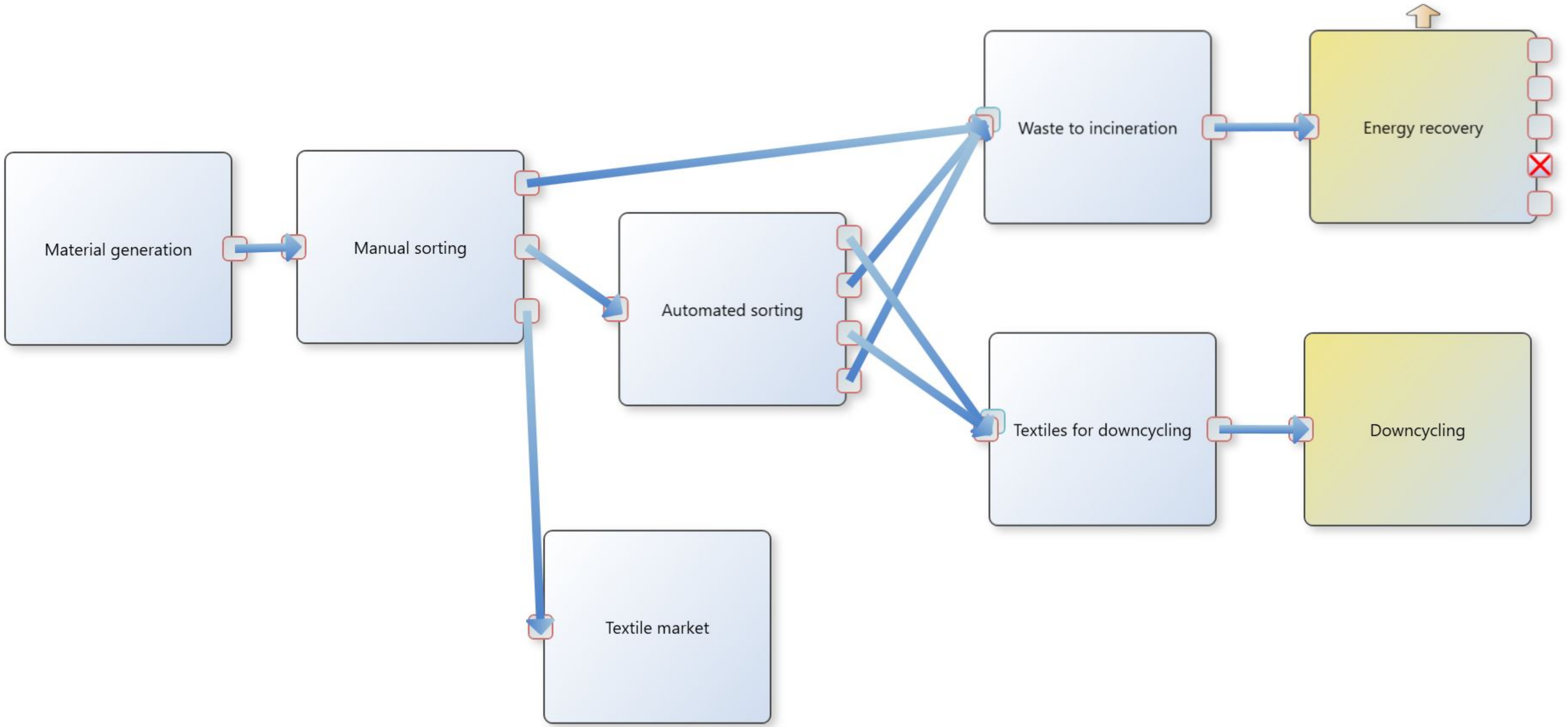

Figure 22: EASETECH model of BAU.

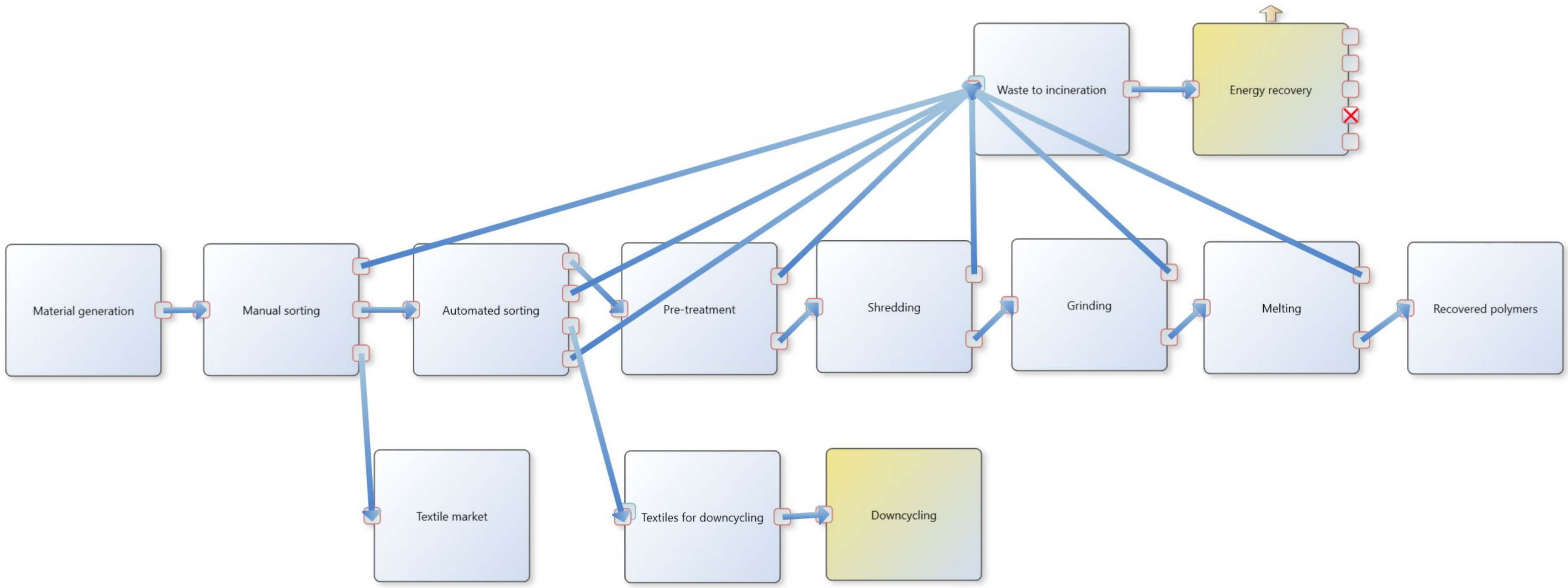

Figure 23: EASETECH model of TM.

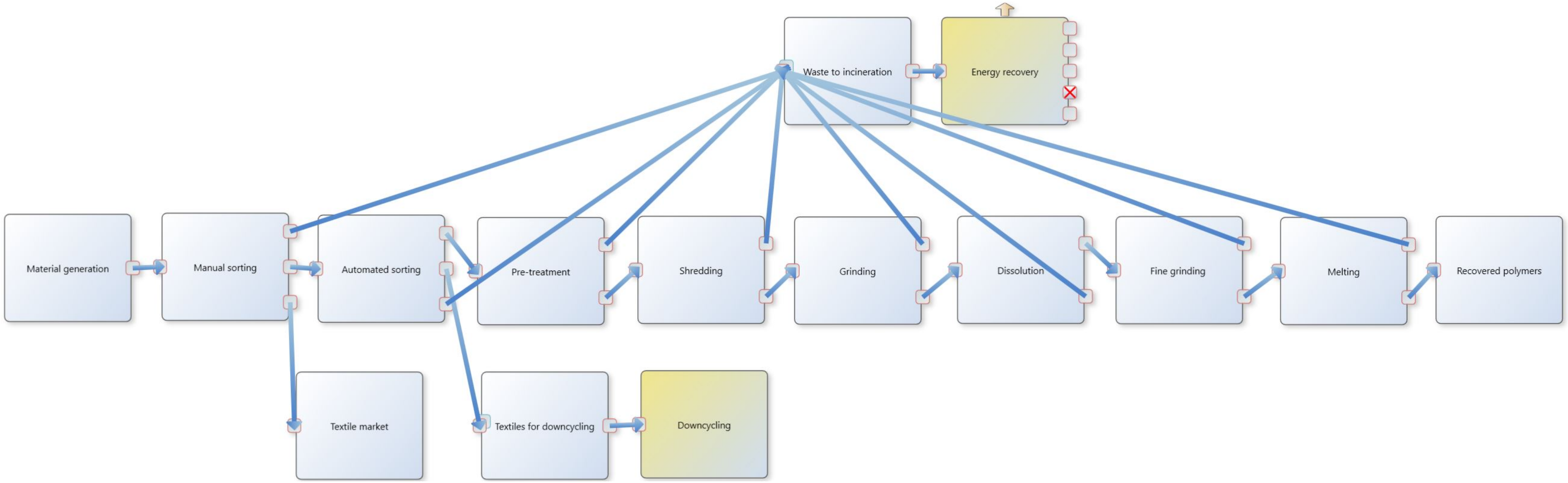

Figure 24: EASETECH model of SD.

C Pedigree matrix

Table 14: Pedigree matrix used to assess the quality of data sources (Weidema et al., 2013).

Indicator score	**1**	**2**	**3**	**4**	**5 (default)**
Reliability	Verified [1] data based on measurements [2]	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g., by industrial expert)	Non-qualified estimate
Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from > 50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (< 50%) relevant for the market considered or > 50% of sites but from shorter periods	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Representativeness unknown or data from a small number of sites and/or from shorter periods
Temporal correlation	Less than 3 years of difference to the time period of the dataset	Less than 6 years of difference to the time period of the dataset	Less than 10 years of difference to the time period of the dataset	Less than 15 years of difference to the time period of the dataset	Age of data unknown or more than 15 years difference to the time period of the dataset
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study (i.e., identical technology) but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials	Data on related processes or laboratory scale or from different technology

[1] Verification may take place in several ways, e.g. by on-site checking, by recalculation, through mass balances or cross-checks with other sources. [2] Includes calculated data (e.g. emissions calculated from inputs to an activity), when the basis for calculation is measurements (e.g. measured inputs). If the calculation is based partly on assumptions, the score would be 2 or 3.

D LCIA results

Table 15: Results of environmental impact for all impact categories for all processes in the BAU alternative.

Process	CC	OD	HTC	HTNC	PM	IR	POF	AC	ET	EF	EM	ECF	LU	WU	RUMM	RUEC
Automated sorting	8.65E+00	1.69E-07	3.62E-08	1.41E-07	2.87E-07	1.43E+00	2.53E-02	3.85E-02	1.05E-01	6.41E-04	7.62E-03	4.05E+01	2.50E+02	1.60E+01	7.72E-05	1.40E+02
Energy recovery	1.92E+02	-7.45E-06	-1.28E-06	-7.94E-06	-6.43E-05	-2.44E+01	-2.07E+00	-5.62E+00	-6.29E+00	-4.62E-02	-5.00E-01	-1.74E+03	-9.12E+03	-2.80E+02	-1.31E-03	-9.18E+03
Manual sorting	2.86E+00	5.54E-08	1.18E-08	4.63E-08	9.70E-08	4.65E-01	8.39E-03	1.29E-02	3.45E-02	2.11E-04	2.52E-03	1.32E+01	8.17E+01	5.19E+00	2.51E-05	4.60E+01
Downcycling	-1.25E+02	4.67E-09	-3.76E-08	-8.64E-07	-4.51E-07	5.31E-01	-3.28E-01	-1.63E-01	-9.47E-01	2.09E-04	-9.62E-02	-2.75E+02	-6.37E+01	4.46E+00	1.94E-05	-9.41E-01
Total	78.17	-7.22E-06	-1.26E-06	-8.61E-06	-6.44E-05	-2.20E+01	-2.37E+00	-5.73E+00	-7.10E+00	-4.51E-02	-5.86E-01	-1.96E+03	-8.86E+03	-2.54E+02	-1.19E-03	-9.00E+03

Table 16: Results of environmental impact for all impact categories for all processes in the TM alternative.

Process	CC	OD	HTC	HTNC	PM	IR	POF	AC	ET	EF	EM	ECF	LU	WU	RUMM	RUEC
Pre-treatment	1.67E-01	3.25E-09	6.93E-10	2.71E-09	5.62E-09	2.73E-02	4.89E-04	7.48E-04	2.02E-03	1.23E-05	1.47E-04	7.75E-01	4.79E+00	3.05E-01	1.47E-06	2.69E+00
Shredding	2.16E+00	4.23E-08	9.05E-09	3.53E-08	7.13E-08	3.57E-01	6.32E-03	9.59E-03	2.61E-02	1.60E-04	1.90E-03	1.01E+01	6.25E+01	3.99E+00	1.93E-05	3.50E+01
Grinding	2.07E+00	4.06E-08	8.68E-09	3.38E-08	6.84E-08	3.43E-01	6.06E-03	9.20E-03	2.51E-02	1.54E-04	1.82E-03	9.70E+00	6.00E+01	3.83E+00	1.85E-05	3.36E+01
Melting	7.89E+00	9.89E-08	1.92E-08	9.27E-08	4.78E-07	6.06E-01	2.45E-02	4.90E-02	8.81E-02	4.81E-04	6.97E-03	2.40E+01	1.35E+02	6.79E+00	3.26E-05	9.98E+01
Energy recovery	2.09E+02	-7.69E-06	-1.32E-06	-8.20E-06	-6.64E-05	-2.52E+01	-2.14E+00	-5.80E+00	-6.50E+00	-4.77E-02	-5.17E-01	-1.80E+03	-9.43E+03	-2.89E+02	-1.35E-03	-9.49E+03
Recovered polymers	-5.26E+02	-2.04E-03	-1.66E-06	-5.50E-06	-2.35E-05	-1.01E+01	-2.18E+00	-2.30E+00	-4.27E+00	-1.73E-02	-3.93E-01	-2.31E+03	-1.64E+03	-1.41E+02	-4.53E-03	-1.08E+04
Manual sorting	2.86E+00	5.54E-08	1.18E-08	4.63E-08	9.70E-08	4.65E-01	8.39E-03	1.29E-02	3.45E-02	2.11E-04	2.52E-03	1.32E+01	8.17E+01	5.19E+00	2.51E-05	4.60E+01
Downcycling	-4.06E+01	1.52E-09	-1.22E-08	-2.81E-07	-1.46E-07	1.72E-01	-1.06E-01	-5.30E-02	-3.07E-01	6.78E-05	-3.12E-02	-8.92E+01	-2.07E+01	1.45E+00	6.30E-06	-3.06E-01
Automated sorting	8.65E+00	1.69E-07	3.62E-08	1.41E-07	2.87E-07	1.43E+00	2.53E-02	3.85E-02	1.05E-01	6.41E-04	7.62E-03	4.05E+01	2.50E+02	1.60E+01	7.72E-05	1.40E+02
Total	-3.34E+02	-2.05E-03	-2.91E-06	-1.36E-05	-8.91E-05	-3.20E+01	-4.35E+00	-8.04E+00	-1.08E+01	-6.32E-02	-9.20E-01	-4.09E+03	-1.05E+04	-3.92E+02	-5.70E-03	-1.99E+04

Table 17: Results of environmental impact for all impact categories for all processes in the SD alternative.

Process	CC	OD	HTC	HTNC	PM	IR	POF	AC	ET	EF	EM	ECF	LU	WU	RUMM	RUEC
Pre-treatment	4.45E-01	8.66E-09	1.85E-09	7.23E-09	1.50E-08	7.28E-02	1.31E-03	2.00E-03	5.38E-03	3.29E-05	3.92E-04	2.07E+00	1.28E+01	8.13E-01	3.93E-06	7.18E+00
Shredding	5.75E+00	1.13E-07	2.41E-08	9.41E-08	1.90E-07	9.53E-01	1.69E-02	2.56E-02	6.98E-02	4.27E-04	5.07E-03	2.70E+01	1.67E+02	1.06E+01	5.15E-05	9.34E+01
Grinding	5.52E+00	1.08E-07	2.32E-08	9.03E-08	1.83E-07	9.15E-01	1.62E-02	2.46E-02	6.70E-02	4.10E-04	4.87E-03	2.59E+01	1.60E+02	1.02E+01	4.94E-05	8.96E+01
Melting	1.96E+01	2.45E-07	4.77E-08	2.30E-07	1.18E-06	1.50E+00	6.07E-02	1.21E-01	2.18E-01	1.19E-03	1.73E-02	5.95E+01	3.34E+02	1.68E+01	8.08E-05	2.48E+02
Energy recovery	1.65E+02	-5.74E-06	-9.82E-07	-6.12E-06	-4.95E-05	-1.88E+01	-1.60E+00	-4.33E+00	-4.85E+00	-3.56E-02	-3.85E-01	-1.34E+03	-7.03E+03	-2.16E+02	-1.01E-03	-7.08E+03
Recovered polymers	-1.30E+03	-5.07E-03	-4.12E-06	-1.36E-05	-5.84E-05	-2.51E+01	-5.40E+00	-5.71E+00	-1.06E+01	-4.28E-02	-9.75E-01	-5.72E+03	-4.06E+03	-3.49E+02	-1.12E-02	-2.67E+04
Manual sorting	2.86E+00	5.54E-08	1.18E-08	4.63E-08	9.70E-08	4.65E-01	8.39E-03	1.29E-02	3.45E-02	2.11E-04	2.52E-03	1.32E+01	8.17E+01	5.19E+00	2.51E-05	4.60E+01
Dissolution	7.91E+02	1.54E-03	1.61E-06	5.69E-06	3.69E-05	6.10E+00	2.45E+00	3.11E+00	5.56E+00	1.86E-02	4.82E-01	5.91E+03	2.05E+03	1.23E+02	3.24E-03	1.08E+04
Fine grinding	5.13E+00	1.01E-07	2.15E-08	8.39E-08	1.70E-07	8.50E-01	1.50E-02	2.28E-02	6.22E-02	3.81E-04	4.52E-03	2.41E+01	1.49E+02	9.50E+00	4.59E-05	8.33E+01
Downcycling	-4.06E+01	1.52E-09	-1.22E-08	-2.81E-07	-1.46E-07	1.72E-01	-1.06E-01	-5.30E-02	-3.07E-01	6.78E-05	-3.12E-02	-8.92E+01	-2.07E+01	1.45E+00	6.30E-06	-3.06E-01
Automated sorting	8.65E+00	1.69E-07	3.62E-08	1.41E-07	2.87E-07	1.43E+00	2.53E-02	3.85E-02	1.05E-01	6.41E-04	7.62E-03	4.05E+01	2.50E+02	1.60E+01	7.72E-05	1.40E+02
Total	-3.42E+02	-3.53E-03	-3.34E-06	-1.37E-05	-6.90E-05	-3.15E+01	-4.51E+00	-6.74E+00	-9.61E+00	-5.64E-02	-8.67E-01	-1.04E+03	-7.91E+03	-3.71E+02	-8.67E-03	-2.23E+04

Table 18: Results of normalised environmental impact for all impact categories for all processes in the TM alternative expressed in Personal Equivalents (PE).

Process	CC	OD	HTC	HTNC	PM	IR	POF	AC	ET	EF	EM	ECF	LU	WU	RUMM	RUEC
Pre-treatment	2.21E-05	6.20E-08	4.00E-05	2.10E-05	9.44E-06	6.46E-06	1.20E-05	1.35E-05	1.14E-05	7.65E-06	7.54E-06	1.37E-05	5.84E-06	2.65E-05	2.32E-05	4.14E-05
Shredding	2.86E-04	8.09E-07	5.23E-04	2.73E-04	1.20E-04	8.46E-05	1.54E-04	1.72E-04	1.48E-04	9.93E-05	9.75E-05	1.78E-04	7.63E-05	3.47E-04	3.03E-04	5.38E-04
Grinding	2.74E-04	7.77E-07	5.02E-04	2.62E-04	1.15E-04	8.12E-05	1.48E-04	1.66E-04	1.42E-04	9.54E-05	9.36E-05	1.71E-04	7.32E-05	3.33E-04	2.91E-04	5.17E-04
Melting	1.04E-03	1.89E-06	1.11E-03	7.19E-04	8.03E-04	1.44E-04	5.99E-04	8.81E-04	4.98E-04	2.99E-04	3.57E-04	4.23E-04	1.65E-04	5.91E-04	5.12E-04	1.54E-03
Energy recovery	2.77E-02	-1.47E-04	-7.61E-02	-6.36E-02	-1.12E-01	-5.98E-03	-5.24E-02	-1.04E-01	-3.67E-02	-2.96E-02	-2.65E-02	-3.17E-02	-1.15E-02	-2.51E-02	-2.13E-02	-1.46E-01
Recovered polymers	-6.97E-02	-3.91E-02	-9.61E-02	-4.27E-02	-3.96E-02	-2.40E-03	-5.32E-02	-4.14E-02	-2.41E-02	-1.07E-02	-2.02E-02	-4.07E-02	-2.00E-03	-1.22E-02	-7.12E-02	-1.66E-01
Manual sorting	3.78E-04	1.06E-06	6.83E-04	3.59E-04	1.63E-04	1.10E-04	2.05E-04	2.31E-04	1.95E-04	1.31E-04	1.29E-04	2.34E-04	9.97E-05	4.52E-04	3.95E-04	7.08E-04
Downcycling	-5.37E-03	2.90E-08	-7.07E-04	-2.18E-03	-2.46E-04	4.09E-05	-2.60E-03	-9.54E-04	-1.74E-03	4.21E-05	-1.60E-03	-1.57E-03	-2.53E-05	1.26E-04	9.91E-05	-4.70E-06
Automated sorting	1.15E-03	3.24E-06	2.09E-03	1.09E-03	4.82E-04	3.39E-04	6.19E-04	6.92E-04	5.92E-04	3.98E-04	3.91E-04	7.14E-04	3.05E-04	1.39E-03	1.21E-03	2.16E-03
Total	-4.43E-02	-3.92E-02	-1.68E-01	-1.06E-01	-1.50E-01	-7.58E-03	-1.06E-01	-1.45E-01	-6.10E-02	-3.93E-02	-4.72E-02	-7.22E-02	-1.28E-02	-3.41E-02	-8.97E-02	-3.06E-01

Table 19: Results of normalised environmental impact for all impact categories for all processes in the SD alternative expressed in Personal Equivalents (PE).

Process	**CC**	**OD**	**HTC**	**HTNC**	**PM**	**IR**	**POF**	**AC**	**ET**	**EF**	**EM**	**ECF**	**LU**	**WU**	**RUMM**	**RUEC**
Pre-treatment	5.89E-05	1.66E-07	1.07E-04	5.60E-05	2.52E-05	1.72E-05	3.19E-05	3.59E-05	3.04E-05	2.04E-05	2.01E-05	3.65E-05	1.56E-05	7.07E-05	6.18E-05	1.10E-04
Shredding	7.62E-04	2.16E-06	1.40E-03	7.29E-04	3.20E-04	2.26E-04	4.12E-04	4.60E-04	3.94E-04	2.65E-04	2.60E-04	4.76E-04	2.04E-04	9.26E-04	8.09E-04	1.44E-03
Grinding	7.32E-04	2.07E-06	1.34E-03	7.00E-04	3.07E-04	2.17E-04	3.96E-04	4.42E-04	3.78E-04	2.54E-04	2.50E-04	4.57E-04	1.95E-04	8.89E-04	7.77E-04	1.38E-03
Melting	2.59E-03	4.69E-06	2.76E-03	1.78E-03	1.99E-03	3.56E-04	1.48E-03	2.18E-03	1.23E-03	7.41E-04	8.86E-04	1.05E-03	4.08E-04	1.46E-03	1.27E-03	3.81E-03
Energy recovery	2.19E-02	-1.10E-04	-5.68E-02	-4.74E-02	-8.32E-02	-4.46E-03	-3.91E-02	-7.78E-02	-2.74E-02	-2.21E-02	-1.98E-02	-2.36E-02	-8.58E-03	-1.88E-02	-1.59E-02	-1.09E-01
Recovered polymers	-1.73E-01	-9.69E-02	-2.38E-01	-1.06E-01	-9.81E-02	-5.96E-03	-1.32E-01	-1.03E-01	-5.98E-02	-2.66E-02	-5.00E-02	-1.01E-01	-4.95E-03	-3.03E-02	-1.77E-01	-4.12E-01
Manual sorting	3.78E-04	1.06E-06	6.83E-04	3.59E-04	1.63E-04	1.10E-04	2.05E-04	2.31E-04	1.95E-04	1.31E-04	1.29E-04	2.34E-04	9.97E-05	4.52E-04	3.95E-04	7.08E-04
Dissolution	1.05E-01	2.94E-02	9.32E-02	4.41E-02	6.20E-02	1.44E-03	5.99E-02	5.58E-02	3.14E-02	1.16E-02	2.47E-02	1.04E-01	2.50E-03	1.07E-02	5.09E-02	1.67E-01
Fine grinding	6.80E-04	1.93E-06	1.24E-03	6.51E-04	2.85E-04	2.01E-04	3.68E-04	4.10E-04	3.52E-04	2.36E-04	2.32E-04	4.24E-04	1.82E-04	8.26E-04	7.22E-04	1.28E-03
Downcycling	-5.37E-03	2.90E-08	-7.07E-04	-2.18E-03	-2.46E-04	4.09E-05	-2.60E-03	-9.54E-04	-1.74E-03	4.21E-05	-1.60E-03	-1.57E-03	-2.53E-05	1.26E-04	9.91E-05	-4.70E-06
Automated sorting	1.15E-03	3.24E-06	2.09E-03	1.09E-03	4.82E-04	3.39E-04	6.19E-04	6.92E-04	5.92E-04	3.98E-04	3.91E-04	7.14E-04	3.05E-04	1.39E-03	1.21E-03	2.16E-03
Total	-4.53E-02	-6.76E-02	-1.93E-01	-1.06E-01	-1.16E-01	-7.47E-03	-1.10E-01	-1.21E-01	-5.43E-02	-3.50E-02	-4.45E-02	-1.83E-02	-9.65E-03	-3.22E-02	-1.36E-01	-3.43E-01

E Sensitivity and data quality

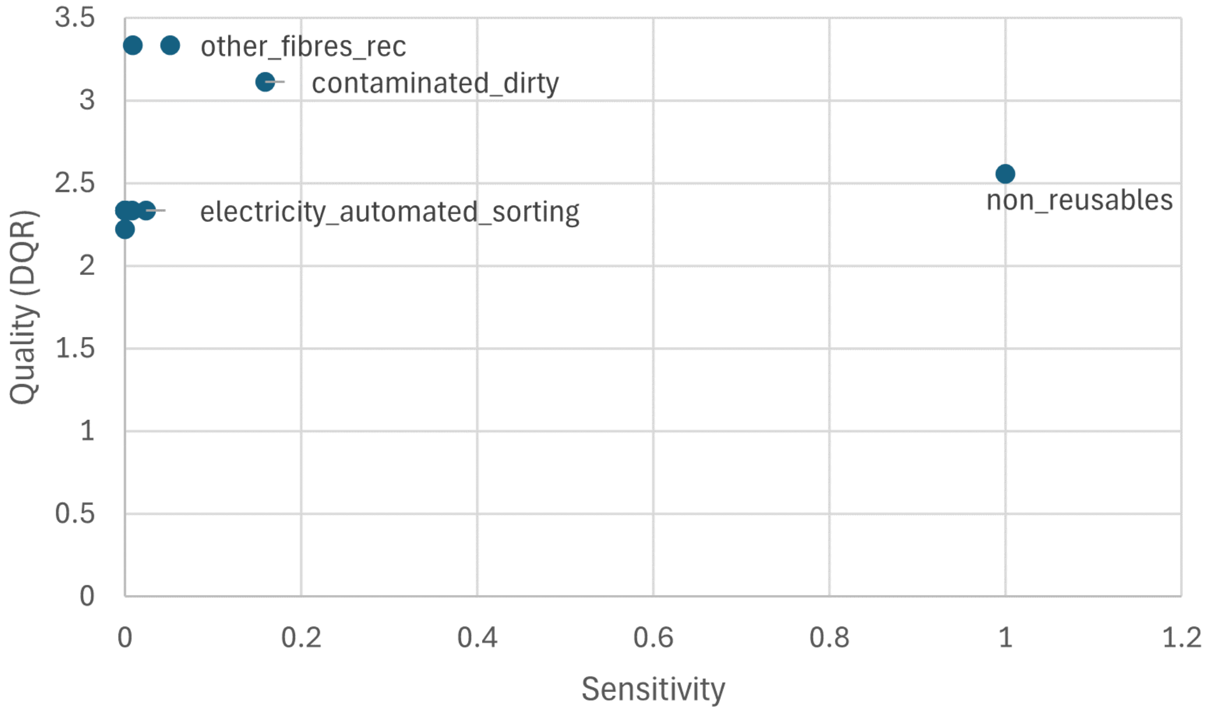

Figure 25: Plot of DQR vs. sensitivity of parameters affecting ecotoxicity freshwater in the BAU alternative. Parameters appearing in the top right-hand corner are identified as key parameters for the impact on ecotoxicity freshwater.

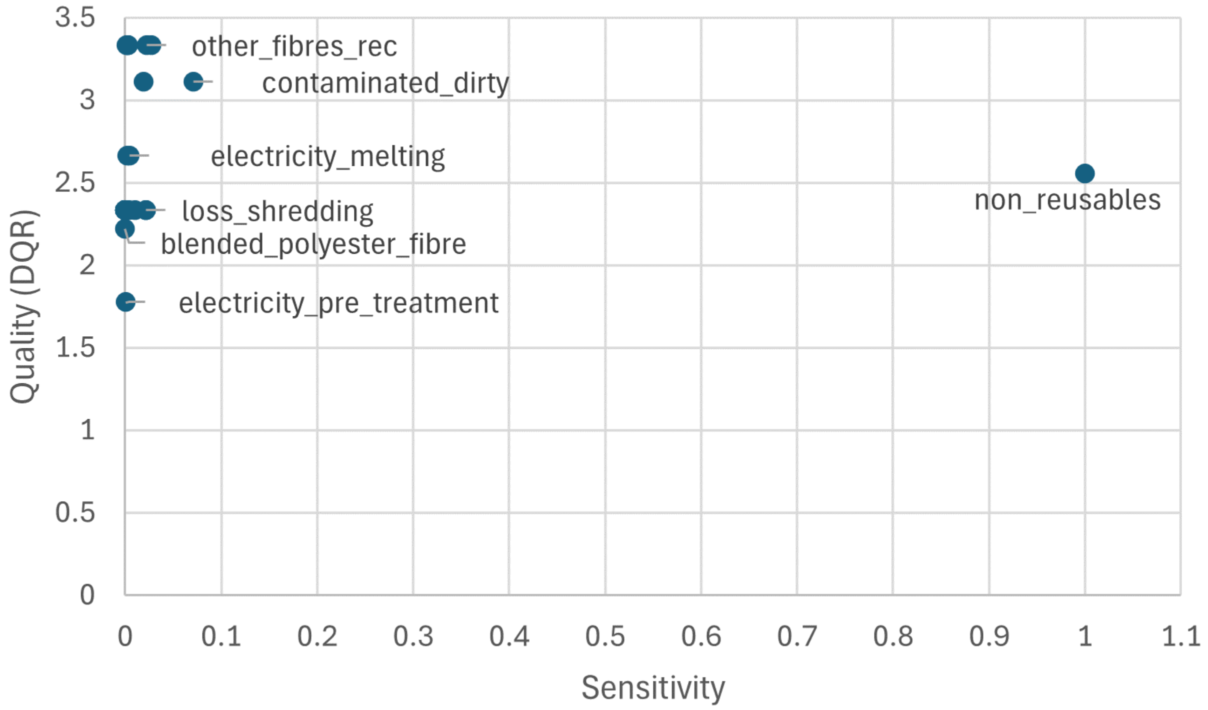

Figure 26: Plot of DQR vs. sensitivity of parameters affecting ecotoxicity freshwater in the TM alternative. Parameters appearing in the top right-hand corner are identified as key parameters for the impact on ecotoxicity freshwater.

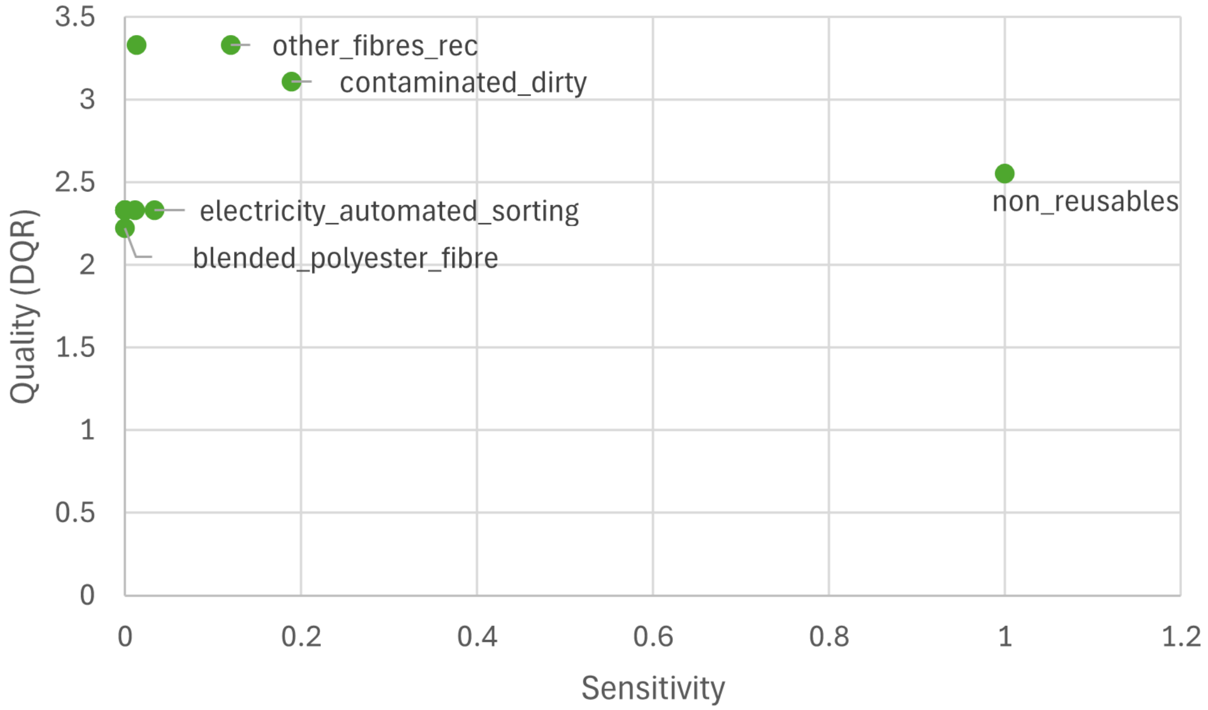

Figure 28: Plot of DQR vs. sensitivity of parameters affecting ecotoxicity freshwater in the BAU alternative. Parameters appearing in the top right-hand corner are identified as key parameters for the impact on land use.

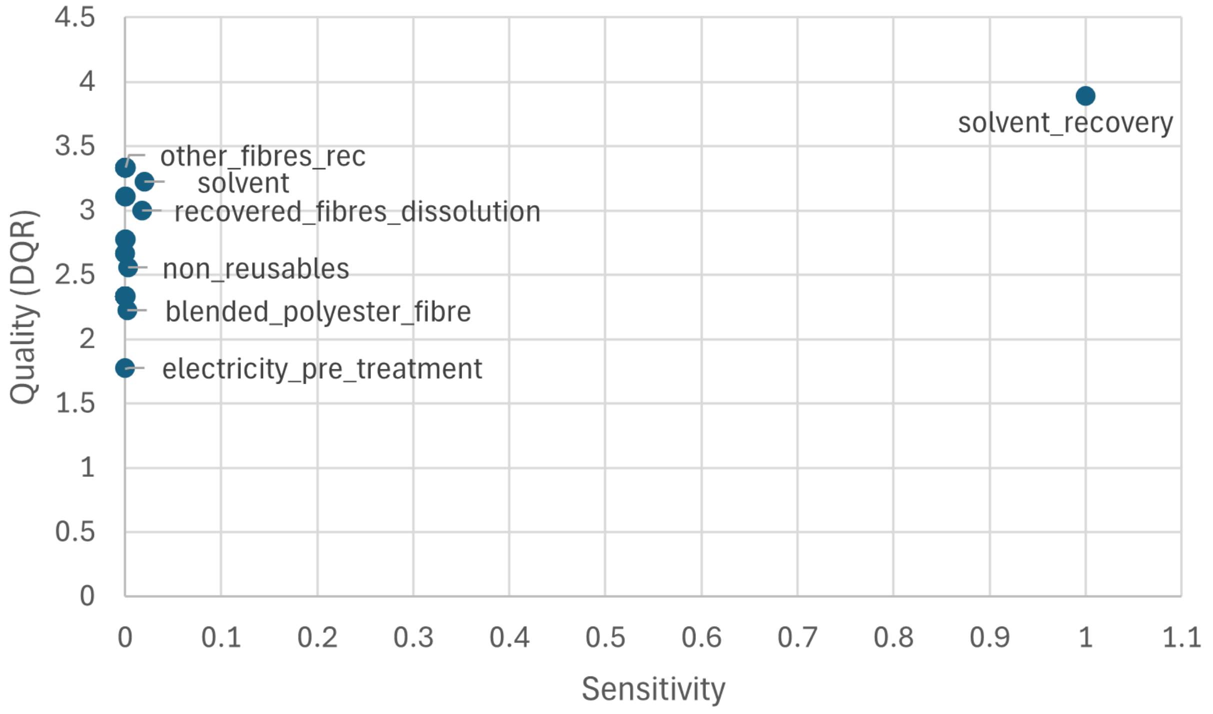

Figure 27: Plot of DQR vs. sensitivity of parameters affecting ecotoxicity freshwater in the SD alternative. Parameters appearing in the top right-hand corner are identified as key parameters for the impact on ecotoxicity freshwater.

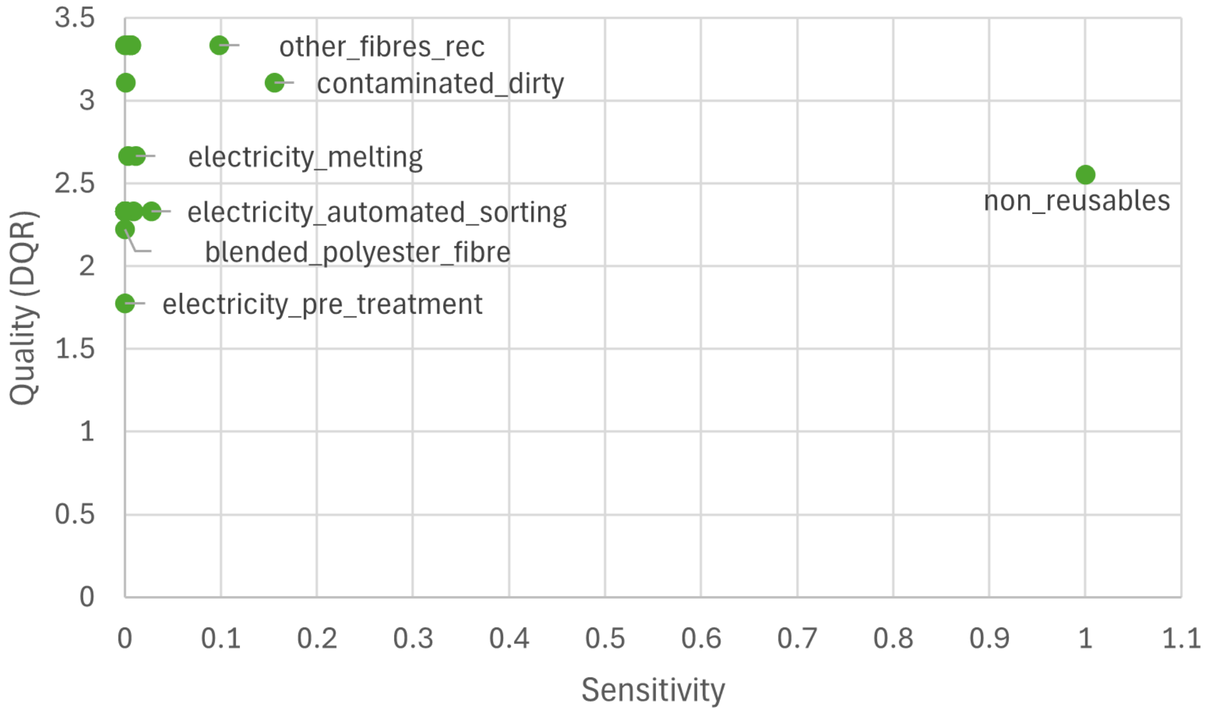

Figure 29: Plot of DQR vs. sensitivity of parameters affecting ecotoxicity freshwater in the TM alternative. Parameters appearing in the top right-hand corner are identified as key parameters for the impact on land use.

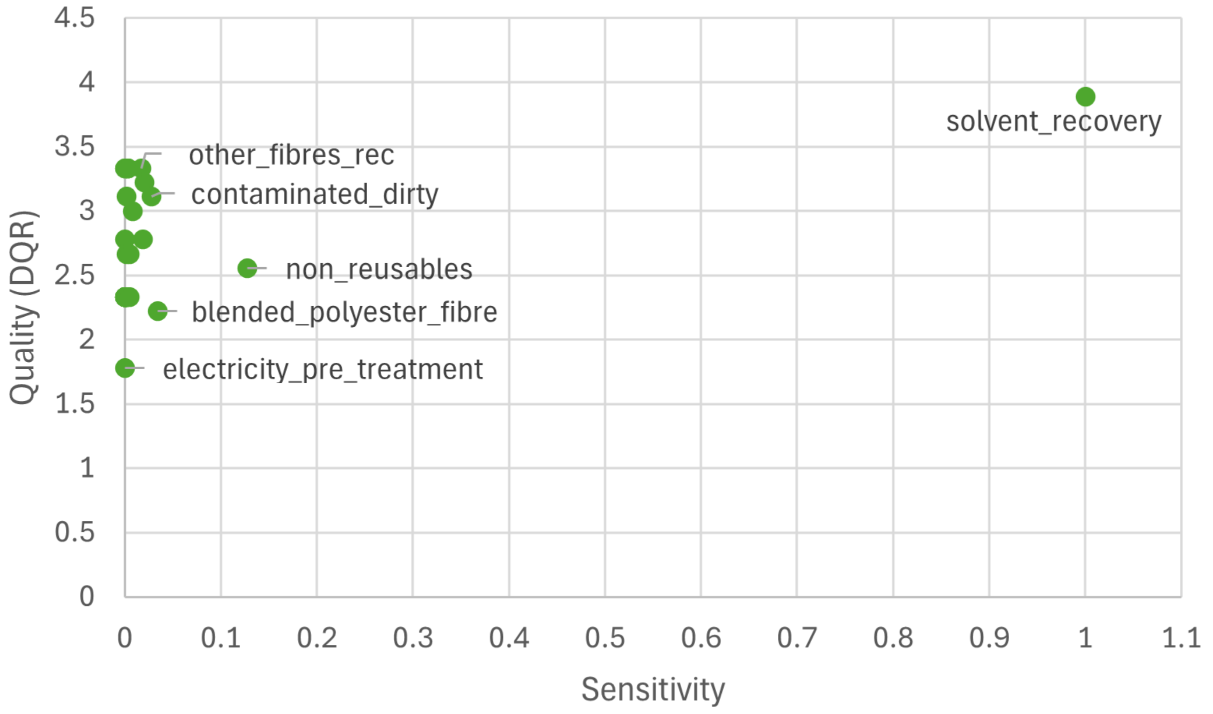

Figure 30: Plot of DQR vs. sensitivity of parameters affecting ecotoxicity freshwater in the SD alternative. Parameters appearing in the top right-hand corner are identified as key parameters for the impact on land use.

Table 26: Results of the data quality ratios for all parameters.

Parameter	**DQR**
contaminated_dirty	3.11
non_reusable	2.56
pure_polyester_fibre	2.22
blended_polyester_fibre	2.22
other_fibres_rec	3.33
loss_findings	3.11
loss_shredding	2.33
loss_grinding	2.33
loss_melting	3.33
loss_fine_grinding	2.33
recovered_fibres_dissolution	3.00
solvent	3.22
solvent_recovery	3.89
electricity_automated_sorting	2.33
electricity_dissolution_process	2.78
electricity_downcycling	3.33
electricity_fine_grinding	3.33
electricity_grinding	3.33
electricity_manual_sorting	2.33
electricity_melting	2.67
electricity_pre_treatment	1.78
electricity_shredding	3.33
heat_automated_sorting	2.33
heat_dissolution_process	2.78
heat_downcycling	2.33
heat_fine_grinding	2.33
heat_grinding	2.33
heat_manual_sorting	2.33
heat_melting	2.67
heat_pre_treatment	2.33
heat_shredding	2.33

Table 27: Results of the data quality ratios for all foreground processes.

Processes	**DQR**
Downcycling	1.80
Dissolution	3.17
Recovered polymers	1.89
Manual sorting	2.39
Automated sorting	2.39
Pre-treatment	2.06
Shredding	3.48
Grinding	3.48
Fine grinding	3.48
Melting	2.67

Table 28: Quality level of data used to validate the identified DQR of parameters and foreground processes. Adapted from the International Reference Life Cycle Data System (ILCD) Handbook - general guide for life cycle assessment - detailed guidance (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010).

Overall data quality rating (DQR)	**Overall data quality level**
≤ 1.6	“High quality”
> 1.6 to ≤ 3	“Basic quality”
> 3 to ≤ 4	“Data estimate”

Table 20: Sensitivity results for the parameters in the BAU alternative.

Parameter	CC	OD	HTC	HTNC	PM	IR	POF	AC	ET	EF	EM	ECF	LU	WU	RUMM	RUEC
blended_polyester_fibre	-1.64E-14	1.17E-15	0.00E+00	1.97E-15	2.11E-15	3.23E-15	5.63E-15	1.55E-15	2.50E-15	0.00E+00	3.79E-15	0.00E+00	2.05E-15	1.12E-15	3.65E-15	2.02E-15
contaminated_dirty	4.87E-01	1.61E-01	1.57E-01	1.44E-01	1.56E-01	1.73E-01	1.37E-01	1.53E-01	1.38E-01	1.60E-01	1.33E-01	1.38E-01	1.61E-01	1.72E-01	1.72E-01	1.59E-01
electricity_automated_sorting	1.10E-01	-2.35E-02	-2.86E-02	-1.64E-02	-4.42E-03	-6.49E-02	-1.07E-02	-6.68E-03	-1.47E-02	-1.42E-02	-1.30E-02	-2.06E-02	-2.82E-02	-6.28E-02	-6.50E-02	-1.56E-02
electricity_downcycling	4.24E-02	-9.01E-03	-1.10E-02	-6.29E-03	-1.70E-03	-2.49E-02	-4.10E-03	-2.57E-03	-5.65E-03	-5.44E-03	-4.98E-03	-7.92E-03	-1.08E-02	-2.41E-02	-2.50E-02	-5.97E-03
electricity_manual_sorting	3.59E-02	-7.63E-03	-9.30E-03	-5.32E-03	-1.44E-03	-2.11E-02	-3.47E-03	-2.17E-03	-4.79E-03	-4.61E-03	-4.21E-03	-6.71E-03	-9.18E-03	-2.04E-02	-2.11E-02	-5.06E-03
heat_automated_sorting	3.19E-04	-2.34E-05	-1.99E-05	-2.32E-05	-3.21E-05	-5.06E-06	-3.42E-05	-3.32E-05	-3.65E-05	-2.78E-05	-3.77E-05	-2.16E-05	-2.08E-05	-5.44E-06	-4.36E-06	-2.70E-05
heat_downcycling	4.29E-05	-3.15E-06	-2.68E-06	-3.12E-06	-4.33E-06	-6.82E-07	-4.60E-06	-4.48E-06	-4.92E-06	-3.75E-06	-5.07E-06	-2.92E-06	-2.80E-06	-7.33E-07	-5.88E-07	-3.64E-06
heat_manual_sorting	6.97E-04	-5.11E-05	-4.35E-05	-5.07E-05	-7.03E-05	-1.11E-05	-7.47E-05	-7.27E-05	-7.98E-05	-6.08E-05	-8.24E-05	-4.73E-05	-4.55E-05	-1.19E-05	-9.55E-06	-5.90E-05
mass_total	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
non_reusable	4.77E-01	8.47E-01	8.52E-01	8.62E-01	8.46E-01	8.48E-01	8.67E-01	8.49E-01	8.67E-01	8.45E-01	8.71E-01	8.68E-01	8.49E-01	8.49E-01	8.49E-01	8.46E-01
other_fibres_rec	-7.54E-01	-1.05E-01	-9.23E-02	-6.06E-02	-9.87E-02	-1.20E-01	-4.36E-02	-8.99E-02	-4.63E-02	-1.05E-01	-3.30E-02	-4.42E-02	-1.02E-01	-1.17E-01	-1.17E-01	-1.03E-01

Table 21: Sensitivity results for the parameters in the TM alternative.

Parameter	**CC**	**OD**	**HTC**	**HTNC**	**PM**	**IR**	**POF**	**AC**	**ET**	**EF**	**EM**	**ECF**	**LU**	**WU**	**RUMM**	**RUEC**
blended_polyester_fibre	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
contaminated_dirty	-1.14E-01	5.67E-04	6.84E-02	9.08E-02	1.13E-01	1.19E-01	7.43E-02	1.09E-01	9.09E-02	1.14E-01	8.48E-02	6.63E-02	1.36E-01	1.11E-01	3.58E-02	7.19E-02
electricity_automated_sorting	-2.58E-02	-8.26E-05	-1.25E-02	-1.03E-02	-3.19E-03	-4.47E-02	-5.80E-03	-4.76E-03	-9.69E-03	-1.01E-02	-8.26E-03	-9.88E-03	-2.38E-02	-4.07E-02	-1.35E-02	-7.03E-03
electricity_downcycling	-3.22E-03	-1.03E-05	-1.55E-03	-1.29E-03	-3.98E-04	-5.57E-03	-7.23E-04	-5.94E-04	-1.21E-03	-1.26E-03	-1.03E-03	-1.23E-03	-2.97E-03	-5.08E-03	-1.69E-03	-8.76E-04
electricity_grinding	-6.19E-03	-1.98E-05	-2.99E-03	-2.48E-03	-7.66E-04	-1.07E-02	-1.39E-03	-1.14E-03	-2.32E-03	-2.43E-03	-1.98E-03	-2.37E-03	-5.72E-03	-9.76E-03	-3.25E-03	-1.69E-03
electricity_manual_sorting	-8.38E-03	-2.69E-05	-4.05E-03	-3.36E-03	-1.04E-03	-1.45E-02	-1.89E-03	-1.55E-03	-3.15E-03	-3.29E-03	-2.68E-03	-3.21E-03	-7.75E-03	-1.32E-02	-4.40E-03	-2.28E-03
electricity_melting	-1.06E-02	-3.39E-05	-5.11E-03	-4.25E-03	-1.31E-03	-1.83E-02	-2.38E-03	-1.96E-03	-3.97E-03	-4.15E-03	-3.39E-03	-4.05E-03	-9.78E-03	-1.67E-02	-5.55E-03	-2.88E-03
electricity_pre_treatment	-4.92E-04	-1.58E-06	-2.38E-04	-1.97E-04	-6.09E-05	-8.52E-04	-1.11E-04	-9.09E-05	-1.85E-04	-1.93E-04	-1.58E-04	-1.88E-04	-4.55E-04	-7.76E-04	-2.58E-04	-1.34E-04
electricity_shredding	-6.44E-03	-2.06E-05	-3.11E-03	-2.59E-03	-7.98E-04	-1.12E-02	-1.45E-03	-1.19E-03	-2.42E-03	-2.53E-03	-2.06E-03	-2.47E-03	-5.96E-03	-1.02E-02	-3.38E-03	-1.76E-03
heat_automated_sorting	-7.45E-05	-8.23E-08	-8.65E-06	-1.47E-05	-2.32E-05	-3.49E-06	-1.86E-05	-2.37E-05	-2.40E-05	-1.98E-05	-2.40E-05	-1.04E-05	-1.76E-05	-3.52E-06	-9.09E-07	-1.22E-05
heat_downcycling	-3.26E-06	-3.60E-09	-3.78E-07	-6.41E-07	-1.02E-06	-1.53E-07	-8.13E-07	-1.04E-06	-1.05E-06	-8.68E-07	-1.05E-06	-4.54E-07	-7.69E-07	-1.54E-07	-3.98E-08	-5.34E-07
heat_grinding	-6.27E-06	-6.93E-09	-7.28E-07	-1.23E-06	-1.95E-06	-2.93E-07	-1.56E-06	-1.99E-06	-2.02E-06	-1.67E-06	-2.02E-06	-8.73E-07	-1.48E-06	-2.97E-07	-7.65E-08	-1.03E-06
heat_manual_sorting	-1.63E-04	-1.80E-07	-1.89E-05	-3.20E-05	-5.08E-05	-7.62E-06	-4.06E-05	-5.18E-05	-5.25E-05	-4.34E-05	-5.25E-05	-2.27E-05	-3.84E-05	-7.71E-06	-1.99E-06	-2.67E-05
heat_melting	-1.30E-02	-1.44E-05	-1.51E-03	-2.56E-03	-4.05E-03	-6.08E-04	-3.24E-03	-4.14E-03	-4.19E-03	-3.46E-03	-4.19E-03	-1.81E-03	-3.07E-03	-6.15E-04	-1.59E-04	-2.13E-03
heat_pre_treatment	-6.78E-06	-7.49E-09	-7.87E-07	-1.33E-06	-2.11E-06	-3.17E-07	-1.69E-06	-2.16E-06	-2.18E-06	-1.81E-06	-2.18E-06	-9.43E-07	-1.60E-06	-3.21E-07	-8.27E-08	-1.11E-06
heat_shredding	-6.53E-06	-7.22E-09	-7.58E-07	-1.28E-06	-2.04E-06	-3.06E-07	-1.63E-06	-2.08E-06	-2.10E-06	-1.74E-06	-2.10E-06	-9.09E-07	-1.54E-06	-3.09E-07	-7.97E-08	-1.07E-06
loss_findings	-6.88E-02	-3.77E-02	-1.82E-02	-1.09E-02	-4.90E-03	-5.33E-03	-1.54E-02	-5.84E-03	-1.06E-02	-4.96E-03	-1.21E-02	-1.81E-02	8.69E-04	-7.38E-03	-2.81E-02	-1.71E-02
loss_grinding	-7.62E-02	-4.15E-02	-2.03E-02	-1.22E-02	-5.45E-03	-6.78E-03	-1.71E-02	-6.52E-03	-1.18E-02	-5.66E-03	-1.35E-02	-2.01E-02	4.69E-04	-8.94E-03	-3.12E-02	-1.90E-02
loss_melting	-9.75E-02	-5.24E-02	-2.60E-02	-1.58E-02	-7.17E-03	-9.56E-03	-2.19E-02	-8.56E-03	-1.54E-02	-7.55E-03	-1.74E-02	-2.57E-02	-8.37E-05	-1.22E-02	-3.97E-02	-2.42E-02
loss_shredding	-7.59E-02	-4.15E-02	-2.02E-02	-1.21E-02	-5.42E-03	-6.33E-03	-1.70E-02	-6.47E-03	-1.17E-02	-5.56E-03	-1.34E-02	-2.00E-02	7.07E-04	-8.54E-03	-3.10E-02	-1.89E-02
mass_total	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
non_reusable	1.12E+00	9.99E-01	9.36E-01	9.13E-01	8.89E-01	8.95E-01	9.28E-01	8.93E-01	9.12E-01	8.89E-01	9.18E-01	9.37E-01	8.72E-01	9.02E-01	9.69E-01	9.30E-01
other_fibres_rec	1.76E-01	-3.68E-04	-4.02E-02	-3.83E-02	-7.13E-02	-8.27E-02	-2.37E-02	-6.41E-02	-3.05E-02	-7.49E-02	-2.10E-02	-2.12E-02	-8.60E-02	-7.59E-02	-2.43E-02	-4.66E-02

Table 22: Sensitivity results for the parameters in the SD alternative.

Parameter	GWP	OD	HTC	HTNC	PM	IR	POF	AC	ET	EF	EM	ECF	LU	WU	RUMM	RUEC
blended_polyester_fibre	1.02E+00	6.24E-01	3.43E-01	1.81E-01	-7.76E-02	7.95E-02	2.67E-01	-5.62E-03	1.19E-01	1.60E-02	1.74E-01	-6.62E-01	-2.24E-01	9.20E-02	5.19E-01	3.18E-01
contaminated_dirty	-1.11E-01	3.29E-04	5.96E-02	9.06E-02	1.45E-01	1.21E-01	7.18E-02	1.30E-01	1.02E-01	1.28E-01	8.99E-02	2.61E-01	1.80E-01	1.18E-01	2.36E-02	6.43E-02
electricity_automated_sorting	-2.52E-02	-4.79E-05	-1.08E-02	-1.03E-02	-4.12E-03	-4.53E-02	-5.60E-03	-5.68E-03	-1.09E-02	-1.13E-02	-8.76E-03	-3.89E-02	-3.16E-02	-4.31E-02	-8.90E-03	-6.28E-03
electricity_dissolution_process	-1.84E-04	-3.50E-07	-7.91E-05	-7.54E-05	-3.01E-05	-3.31E-04	-4.09E-05	-4.15E-05	-7.94E-05	-8.28E-05	-6.40E-05	-2.84E-04	-2.31E-04	-3.14E-04	-6.50E-05	-4.59E-05
electricity_downcycling	-3.15E-03	-5.98E-06	-1.35E-03	-1.29E-03	-5.14E-04	-5.66E-03	-6.99E-04	-7.09E-04	-1.36E-03	-1.41E-03	-1.09E-03	-4.85E-03	-3.94E-03	-5.37E-03	-1.11E-03	-7.84E-04
electricity_fine_grinding	-1.50E-02	-2.85E-05	-6.45E-03	-6.14E-03	-2.45E-03	-2.70E-02	-3.33E-03	-3.38E-03	-6.47E-03	-6.74E-03	-5.21E-03	-2.31E-02	-1.88E-02	-2.56E-02	-5.30E-03	-3.74E-03
electricity_grinding	-1.61E-02	-3.07E-05	-6.94E-03	-6.61E-03	-2.64E-03	-2.90E-02	-3.59E-03	-3.64E-03	-6.96E-03	-7.26E-03	-5.61E-03	-2.49E-02	-2.02E-02	-2.76E-02	-5.70E-03	-4.02E-03
electricity_manual_sorting	-8.20E-03	-1.56E-05	-3.52E-03	-3.36E-03	-1.34E-03	-1.47E-02	-1.82E-03	-1.85E-03	-3.53E-03	-3.69E-03	-2.85E-03	-1.26E-02	-1.03E-02	-1.40E-02	-2.89E-03	-2.04E-03
electricity_melting	-2.57E-02	-4.88E-05	-1.10E-02	-1.05E-02	-4.20E-03	-4.61E-02	-5.70E-03	-5.78E-03	-1.11E-02	-1.15E-02	-8.91E-03	-3.96E-02	-3.22E-02	-4.38E-02	-9.06E-03	-6.39E-03
electricity_pre_treatment	-1.28E-03	-2.44E-06	-5.52E-04	-5.25E-04	-2.10E-04	-2.31E-03	-2.85E-04	-2.89E-04	-5.53E-04	-5.77E-04	-4.46E-04	-1.98E-03	-1.61E-03	-2.19E-03	-4.53E-04	-3.20E-04
electricity_shredding	-1.68E-02	-3.19E-05	-7.23E-03	-6.88E-03	-2.75E-03	-3.02E-02	-3.74E-03	-3.79E-03	-7.25E-03	-7.56E-03	-5.84E-03	-2.59E-02	-2.11E-02	-2.87E-02	-5.94E-03	-4.19E-03
heat_automated_sorting	-7.29E-05	-4.77E-08	-7.53E-06	-1.46E-05	-3.00E-05	-3.54E-06	-1.80E-05	-2.83E-05	-2.69E-05	-2.22E-05	-2.54E-05	-4.08E-05	-2.33E-05	-3.73E-06	-5.98E-07	-1.09E-05
heat_dissolution_process	-3.93E-01	-2.57E-04	-4.06E-02	-7.88E-02	-1.62E-01	-1.91E-02	-9.68E-02	-1.52E-01	-1.45E-01	-1.20E-01	-1.37E-01	-2.20E-01	-1.26E-01	-2.01E-02	-3.22E-03	-5.88E-02
heat_downcycling	-3.19E-06	-2.09E-09	-3.29E-07	-6.40E-07	-1.31E-06	-1.55E-07	-7.86E-07	-1.24E-06	-1.18E-06	-9.73E-07	-1.11E-06	-1.79E-06	-1.02E-06	-1.63E-07	-2.62E-08	-4.77E-07
heat_fine_grinding	-1.52E-05	-9.97E-09	-1.57E-06	-3.05E-06	-6.25E-06	-7.38E-07	-3.75E-06	-5.90E-06	-5.62E-06	-4.64E-06	-5.31E-06	-8.52E-06	-4.86E-06	-7.78E-07	-1.25E-07	-2.28E-06
heat_grinding	-1.64E-05	-1.07E-08	-1.69E-06	-3.28E-06	-6.73E-06	-7.94E-07	-4.03E-06	-6.35E-06	-6.05E-06	-4.99E-06	-5.71E-06	-9.16E-06	-5.23E-06	-8.38E-07	-1.34E-07	-2.45E-06
heat_manual_sorting	-1.59E-04	-1.04E-07	-1.65E-05	-3.20E-05	-6.55E-05	-7.74E-06	-3.93E-05	-6.18E-05	-5.90E-05	-4.86E-05	-5.57E-05	-8.93E-05	-5.10E-05	-8.16E-06	-1.31E-06	-2.39E-05
heat_melting	-3.16E-02	-2.07E-05	-3.26E-03	-6.33E-03	-1.30E-02	-1.53E-03	-7.77E-03	-1.22E-02	-1.17E-02	-9.62E-03	-1.10E-02	-1.77E-02	-1.01E-02	-1.61E-03	-2.59E-04	-4.72E-03
heat_pre_treatment	-1.77E-05	-1.16E-08	-1.83E-06	-3.55E-06	-7.28E-06	-8.59E-07	-4.36E-06	-6.86E-06	-6.54E-06	-5.40E-06	-6.18E-06	-9.91E-06	-5.66E-06	-9.06E-07	-1.45E-07	-2.65E-06
heat_shredding	-1.71E-05	-1.12E-08	-1.76E-06	-3.42E-06	-7.01E-06	-8.27E-07	-4.20E-06	-6.61E-06	-6.30E-06	-5.20E-06	-5.95E-06	-9.55E-06	-5.45E-06	-8.72E-07	-1.40E-07	-2.55E-06
loss_findings	-6.81E-02	-3.78E-02	-2.08E-02	-1.10E-02	4.69E-03	-4.91E-03	-1.62E-02	3.29E-04	-7.23E-03	-9.93E-04	-1.05E-02	4.00E-02	1.35E-02	-5.66E-03	-3.14E-02	-1.93E-02
loss_fine_grinding	-1.73E-01	-5.97E-02	-4.39E-02	-3.03E-02	-1.75E-02	-1.71E-02	-4.09E-02	-1.93E-02	-3.29E-02	-1.57E-02	-3.54E-02	-1.96E-01	1.54E-03	-2.35E-02	-5.08E-02	-4.20E-02
loss_grinding	-7.63E-02	-4.16E-02	-2.35E-02	-1.27E-02	4.93E-03	-7.87E-03	-1.81E-02	5.19E-05	-8.55E-03	-1.71E-03	-1.21E-02	4.19E-02	1.31E-02	-8.57E-03	-3.51E-02	-2.16E-02
loss_melting	-2.22E-01	-7.54E-02	-5.62E-02	-3.91E-02	-2.30E-02	-2.40E-02	-5.24E-02	-2.53E-02	-4.28E-02	-2.10E-02	-4.58E-02	-2.51E-01	-2.75E-04	-3.20E-02	-6.47E-02	-5.37E-02
loss_shredding	-7.57E-02	-4.16E-02	-2.32E-02	-1.24E-02	5.04E-03	-6.66E-03	-1.80E-02	2.04E-04	-8.26E-03	-1.41E-03	-1.18E-02	4.30E-02	1.39E-02	-7.42E-03	-3.48E-02	-2.14E-02
mass_total	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
non_reusable	1.12E+00	1.00E+00	9.44E-01	9.13E-01	8.56E-01	8.94E-01	9.30E-01	8.72E-01	9.02E-01	8.76E-01	9.13E-01	7.52E-01	8.30E-01	8.96E-01	9.79E-01	9.38E-01
other_fibres_rec	1.73E-01	-2.14E-04	-3.50E-02	-3.82E-02	-9.21E-02	-8.39E-02	-2.29E-02	-7.64E-02	-3.42E-02	-8.40E-02	-2.23E-02	-8.34E-02	-1.14E-01	-8.03E-02	-1.60E-02	-4.17E-02
recovered_fibres_dissolution	4.15E+00	1.43E+00	1.05E+00	7.20E-01	4.16E-01	3.82E-01	9.78E-01	4.59E-01	7.83E-01	3.71E-01	8.45E-01	4.68E+00	-5.58E-02	5.38E-01	1.22E+00	1.00E+00
solvent	-1.92E+00	-4.35E-01	-4.42E-01	-3.37E-01	-3.73E-01	-1.74E-01	-4.47E-01	-3.08E-01	-4.33E-01	-2.10E-01	-4.18E-01	-5.47E+00	-1.33E-01	-3.12E-01	-3.70E-01	-4.28E-01
solvent_recovery	9.41E+01	2.13E+01	2.17E+01	1.65E+01	1.83E+01	8.53E+00	2.19E+01	1.51E+01	2.12E+01	1.03E+01	2.05E+01	2.68E+02	6.51E+00	1.53E+01	1.81E+01	2.10E+01

Table 23: Normalised sensitivity results for the parameters in the BAU alternative. Red coloured boxes indicate high sensitivity, green coloured boxes indicate low sensitivity, and the other colours represent varying degrees of sensitivity in between.

Parameter	**CC**	**OD**	**HTC**	**HTNC**	**PM**	**IR**	**POF**	**AC**	**ET**	**EF**	**EM**	**ECF**	**LU**	**WU**	**RUMM**	**RUEC**
blended_polyester_fibre	2.17E-14	1.39E-15	0.00E+00	2.28E-15	2.49E-15	3.81E-15	6.49E-15	1.83E-15	2.89E-15	0.00E+00	4.35E-15	0.00E+00	2.42E-15	1.32E-15	4.30E-15	2.39E-15
contaminated_dirty	6.46E-01	1.90E-01	1.85E-01	1.67E-01	1.84E-01	2.04E-01	1.58E-01	1.80E-01	1.60E-01	1.89E-01	1.53E-01	1.59E-01	1.89E-01	2.02E-01	2.03E-01	1.88E-01
electricity_automated_sorting	1.46E-01	2.77E-02	3.36E-02	1.90E-02	5.23E-03	7.66E-02	1.23E-02	7.87E-03	1.70E-02	1.68E-02	1.49E-02	2.37E-02	3.33E-02	7.40E-02	7.65E-02	1.84E-02
electricity_downcycling	5.62E-02	1.06E-02	1.29E-02	7.30E-03	2.01E-03	2.94E-02	4.73E-03	3.02E-03	6.53E-03	6.44E-03	5.71E-03	9.12E-03	1.28E-02	2.84E-02	2.94E-02	7.06E-03
electricity_manual_sorting	4.75E-02	9.01E-03	1.09E-02	6.18E-03	1.70E-03	2.49E-02	4.00E-03	2.56E-03	5.52E-03	5.45E-03	4.84E-03	7.72E-03	1.08E-02	2.40E-02	2.49E-02	5.98E-03
heat_automated_sorting	4.23E-04	2.76E-05	2.33E-05	2.69E-05	3.80E-05	5.97E-06	3.94E-05	3.91E-05	4.21E-05	3.29E-05	4.32E-05	2.49E-05	2.45E-05	6.40E-06	5.14E-06	3.19E-05
heat_downcycling	5.69E-05	3.72E-06	3.14E-06	3.63E-06	5.12E-06	8.05E-07	5.31E-06	5.28E-06	5.67E-06	4.43E-06	5.82E-06	3.36E-06	3.30E-06	8.63E-07	6.93E-07	4.30E-06
heat_manual_sorting	9.24E-04	6.04E-05	5.10E-05	5.88E-05	8.31E-05	1.31E-05	8.62E-05	8.56E-05	9.21E-05	7.20E-05	9.45E-05	5.45E-05	5.36E-05	1.40E-05	1.12E-05	6.98E-05
non_reusable	6.32E-01	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
other_fibres_rec	1.00E+00	1.23E-01	1.08E-01	7.03E-02	1.17E-01	1.42E-01	5.03E-02	1.06E-01	5.34E-02	1.24E-01	3.79E-02	5.09E-02	1.20E-01	1.38E-01	1.38E-01	1.22E-01

Table 24: Normalised sensitivity results for the parameters in the TM alternative. Red coloured boxes indicate high sensitivity, green coloured boxes indicate low sensitivity, and the other colours represent varying degrees of sensitivity in between.

Parameter	CC	OD	HTC	HTNC	PM	IR	POF	AC	ET	EF	EM	ECF	LU	WU	RUMM	RUEC
blended_polyester_fibre	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
contaminated_dirty	1.01E-01	5.67E-04	7.31E-02	9.95E-02	1.27E-01	1.33E-01	8.01E-02	1.22E-01	9.97E-02	1.28E-01	9.24E-02	7.08E-02	1.56E-01	1.23E-01	3.70E-02	7.73E-02
electricity_automated_sorting	2.30E-02	8.26E-05	1.33E-02	1.13E-02	3.59E-03	4.99E-02	6.25E-03	5.34E-03	1.06E-02	1.14E-02	9.00E-03	1.05E-02	2.73E-02	4.51E-02	1.40E-02	7.55E-03
electricity_downcycling	2.87E-03	1.03E-05	1.66E-03	1.41E-03	4.48E-04	6.23E-03	7.80E-04	6.66E-04	1.32E-03	1.42E-03	1.12E-03	1.32E-03	3.41E-03	5.63E-03	1.74E-03	9.42E-04
electricity_grinding	5.51E-03	1.98E-05	3.19E-03	2.72E-03	8.62E-04	1.20E-02	1.50E-03	1.28E-03	2.55E-03	2.73E-03	2.16E-03	2.53E-03	6.56E-03	1.08E-02	3.35E-03	1.81E-03
electricity_manual_sorting	7.47E-03	2.69E-05	4.33E-03	3.69E-03	1.17E-03	1.62E-02	2.03E-03	1.74E-03	3.45E-03	3.70E-03	2.92E-03	3.43E-03	8.89E-03	1.47E-02	4.54E-03	2.46E-03
electricity_melting	9.43E-03	3.39E-05	5.46E-03	4.65E-03	1.48E-03	2.05E-02	2.57E-03	2.19E-03	4.36E-03	4.67E-03	3.69E-03	4.33E-03	1.12E-02	1.85E-02	5.73E-03	3.10E-03
electricity_pre_treatment	4.38E-04	1.58E-06	2.54E-04	2.16E-04	6.86E-05	9.52E-04	1.19E-04	1.02E-04	2.03E-04	2.17E-04	1.72E-04	2.01E-04	5.21E-04	8.61E-04	2.67E-04	1.44E-04
electricity_shredding	5.74E-03	2.06E-05	3.33E-03	2.83E-03	8.98E-04	1.25E-02	1.56E-03	1.33E-03	2.65E-03	2.84E-03	2.25E-03	2.63E-03	6.83E-03	1.13E-02	3.49E-03	1.89E-03
heat_automated_sorting	6.64E-05	8.24E-08	9.24E-06	1.61E-05	2.61E-05	3.89E-06	2.00E-05	2.65E-05	2.63E-05	2.23E-05	2.61E-05	1.11E-05	2.01E-05	3.91E-06	9.39E-07	1.31E-05
heat_downcycling	2.91E-06	3.60E-09	4.04E-07	7.03E-07	1.14E-06	1.70E-07	8.77E-07	1.16E-06	1.15E-06	9.76E-07	1.14E-06	4.84E-07	8.81E-07	1.71E-07	4.11E-08	5.74E-07
heat_grinding	5.59E-06	6.93E-09	7.78E-07	1.35E-06	2.20E-06	3.28E-07	1.69E-06	2.23E-06	2.22E-06	1.88E-06	2.20E-06	9.31E-07	1.70E-06	3.29E-07	7.90E-08	1.10E-06
heat_manual_sorting	1.45E-04	1.80E-07	2.02E-05	3.51E-05	5.71E-05	8.51E-06	4.38E-05	5.81E-05	5.76E-05	4.88E-05	5.72E-05	2.42E-05	4.41E-05	8.55E-06	2.05E-06	2.87E-05
heat_melting	1.16E-02	1.44E-05	1.61E-03	2.80E-03	4.56E-03	6.79E-04	3.50E-03	4.63E-03	4.59E-03	3.89E-03	4.56E-03	1.93E-03	3.52E-03	6.82E-04	1.64E-04	2.29E-03
heat_pre_treatment	6.04E-06	7.49E-09	8.41E-07	1.46E-06	2.38E-06	3.54E-07	1.82E-06	2.42E-06	2.39E-06	2.03E-06	2.38E-06	1.01E-06	1.83E-06	3.56E-07	8.54E-08	1.19E-06
heat_shredding	5.82E-06	7.22E-09	8.10E-07	1.41E-06	2.29E-06	3.41E-07	1.76E-06	2.33E-06	2.31E-06	1.96E-06	2.29E-06	9.70E-07	1.77E-06	3.43E-07	8.23E-08	1.15E-06
loss_findings	6.13E-02	3.77E-02	1.95E-02	1.20E-02	5.51E-03	5.96E-03	1.66E-02	6.54E-03	1.16E-02	5.57E-03	1.32E-02	1.93E-02	9.96E-04	8.18E-03	2.90E-02	1.84E-02
loss_grinding	6.79E-02	4.15E-02	2.17E-02	1.34E-02	6.14E-03	7.57E-03	1.84E-02	7.31E-03	1.30E-02	6.36E-03	1.47E-02	2.14E-02	5.38E-04	9.92E-03	3.22E-02	2.04E-02
loss_melting	8.68E-02	5.24E-02	2.78E-02	1.73E-02	8.07E-03	1.07E-02	2.36E-02	9.59E-03	1.68E-02	8.49E-03	1.90E-02	2.74E-02	9.60E-05	1.35E-02	4.10E-02	2.60E-02
loss_shredding	6.76E-02	4.15E-02	2.16E-02	1.33E-02	6.10E-03	7.07E-03	1.83E-02	7.25E-03	1.29E-02	6.25E-03	1.46E-02	2.13E-02	8.11E-04	9.47E-03	3.20E-02	2.03E-02
non_reusable	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
other_fibres_rec	1.57E-01	3.68E-04	4.29E-02	4.20E-02	8.03E-02	9.23E-02	2.56E-02	7.18E-02	3.34E-02	8.42E-02	2.29E-02	2.26E-02	9.86E-02	8.41E-02	2.51E-02	5.01E-02

Table 25: Normalised sensitivity results for the parameters in the SD alternative. Red coloured boxes indicate high sensitivity, green coloured boxes indicate low sensitivity, and the other colours represent varying degrees of sensitivity in between.

Parameter	CC	OD	HTC	HTNC	PM	IR	POF	AC	ET	EF	EM	ECF	LU	WU	RUMM	RUEC
blended_polyester_fibre	1.08E-02	2.93E-02	1.58E-02	1.10E-02	4.24E-03	9.33E-03	1.22E-02	3.72E-04	5.62E-03	1.56E-03	8.47E-03	2.47E-03	3.43E-02	6.02E-03	2.86E-02	1.52E-02
contaminated_dirty	1.18E-03	1.54E-05	2.75E-03	5.48E-03	7.94E-03	1.42E-02	3.28E-03	8.61E-03	4.82E-03	1.24E-02	4.39E-03	9.74E-04	2.77E-02	7.71E-03	1.30E-03	3.07E-03
electricity_automated_sorting	2.68E-04	2.25E-06	5.00E-04	6.24E-04	2.25E-04	5.32E-03	2.56E-04	3.76E-04	5.13E-04	1.10E-03	4.27E-04	1.45E-04	4.86E-03	2.82E-03	4.91E-04	3.00E-04
electricity_dissolution_process	1.96E-06	1.64E-08	3.65E-06	4.56E-06	1.65E-06	3.88E-05	1.87E-06	2.75E-06	3.74E-06	8.06E-06	3.12E-06	1.06E-06	3.55E-05	2.06E-05	3.59E-06	2.19E-06
electricity_downcycling	3.34E-05	2.81E-07	6.24E-05	7.79E-05	2.81E-05	6.63E-04	3.19E-05	4.69E-05	6.40E-05	1.38E-04	5.33E-05	1.81E-05	6.06E-04	3.52E-04	6.13E-05	3.74E-05
electricity_fine_grinding	1.59E-04	1.34E-06	2.97E-04	3.71E-04	1.34E-04	3.16E-03	1.52E-04	2.24E-04	3.05E-04	6.56E-04	2.54E-04	8.63E-05	2.89E-03	1.68E-03	2.92E-04	1.78E-04
electricity_grinding	1.72E-04	1.44E-06	3.20E-04	4.00E-04	1.44E-04	3.40E-03	1.64E-04	2.41E-04	3.28E-04	7.06E-04	2.73E-04	9.29E-05	3.11E-03	1.81E-03	3.14E-04	1.92E-04
electricity_manual_sorting	8.72E-05	7.32E-07	1.63E-04	2.03E-04	7.33E-05	1.73E-03	8.31E-05	1.22E-04	1.67E-04	3.59E-04	1.39E-04	4.72E-05	1.58E-03	9.17E-04	1.60E-04	9.74E-05
electricity_melting	2.73E-04	2.29E-06	5.09E-04	6.36E-04	2.29E-04	5.41E-03	2.60E-04	3.83E-04	5.22E-04	1.12E-03	4.35E-04	1.48E-04	4.94E-03	2.87E-03	5.00E-04	3.05E-04
electricity_pre_treatment	1.36E-05	1.15E-07	2.54E-05	3.18E-05	1.15E-05	2.71E-04	1.30E-05	1.91E-05	2.61E-05	5.62E-05	2.17E-05	7.39E-06	2.47E-04	1.44E-04	2.50E-05	1.53E-05
electricity_shredding	1.79E-04	1.50E-06	3.33E-04	4.16E-04	1.50E-04	3.54E-03	1.71E-04	2.51E-04	3.42E-04	7.36E-04	2.85E-04	9.68E-05	3.24E-03	1.88E-03	3.27E-04	2.00E-04
heat_automated_sorting	7.75E-07	2.24E-09	3.47E-07	8.84E-07	1.64E-06	4.15E-07	8.19E-07	1.87E-06	1.27E-06	2.16E-06	1.24E-06	1.52E-07	3.58E-06	2.44E-07	3.30E-08	5.20E-07
heat_dissolution_process	4.18E-03	1.21E-05	1.87E-03	4.77E-03	8.83E-03	2.23E-03	4.42E-03	1.01E-02	6.85E-03	1.17E-02	6.69E-03	8.21E-04	1.93E-02	1.32E-03	1.78E-04	2.80E-03
heat_downcycling	3.39E-08	9.81E-11	1.52E-08	3.87E-08	7.17E-08	1.81E-08	3.59E-08	8.19E-08	5.56E-08	9.47E-08	5.43E-08	6.67E-09	1.57E-07	1.07E-08	1.44E-09	2.28E-08
heat_fine_grinding	1.62E-07	4.68E-10	7.25E-08	1.85E-07	3.42E-07	8.65E-08	1.71E-07	3.90E-07	2.65E-07	4.52E-07	2.59E-07	3.18E-08	7.47E-07	5.10E-08	6.89E-09	1.09E-07
heat_grinding	1.74E-07	5.04E-10	7.80E-08	1.99E-07	3.68E-07	9.31E-08	1.84E-07	4.20E-07	2.86E-07	4.86E-07	2.79E-07	3.42E-08	8.04E-07	5.48E-08	7.41E-09	1.17E-07
heat_manual_sorting	1.69E-06	4.91E-09	7.60E-07	1.93E-06	3.58E-06	9.07E-07	1.79E-06	4.09E-06	2.78E-06	4.73E-06	2.71E-06	3.33E-07	7.83E-06	5.34E-07	7.22E-08	1.14E-06
heat_melting	3.35E-04	9.71E-07	1.50E-04	3.83E-04	7.09E-04	1.79E-04	3.55E-04	8.10E-04	5.50E-04	9.37E-04	5.37E-04	6.59E-05	1.55E-03	1.06E-04	1.43E-05	2.25E-04
heat_pre_treatment	1.88E-07	5.45E-10	8.43E-08	2.15E-07	3.98E-07	1.01E-07	1.99E-07	4.54E-07	3.09E-07	5.25E-07	3.01E-07	3.70E-08	8.69E-07	5.93E-08	8.01E-09	1.26E-07
heat_shredding	1.81E-07	5.25E-10	8.12E-08	2.07E-07	3.83E-07	9.70E-08	1.92E-07	4.38E-07	2.97E-07	5.06E-07	2.90E-07	3.56E-08	8.37E-07	5.71E-08	7.72E-09	1.22E-07
loss_findings	7.24E-04	1.77E-03	9.59E-04	6.66E-04	2.56E-04	5.75E-04	7.39E-04	2.18E-05	3.41E-04	9.67E-05	5.14E-04	1.49E-04	2.07E-03	3.70E-04	1.73E-03	9.21E-04
loss_fine_grinding	1.84E-03	2.80E-03	2.02E-03	1.83E-03	9.54E-04	2.00E-03	1.87E-03	1.28E-03	1.55E-03	1.53E-03	1.73E-03	7.32E-04	2.37E-04	1.54E-03	2.80E-03	2.00E-03
loss_grinding	8.11E-04	1.95E-03	1.08E-03	7.66E-04	2.70E-04	9.22E-04	8.26E-04	3.44E-06	4.03E-04	1.66E-04	5.89E-04	1.56E-04	2.01E-03	5.61E-04	1.93E-03	1.03E-03
loss_melting	2.36E-03	3.54E-03	2.59E-03	2.37E-03	1.25E-03	2.82E-03	2.39E-03	1.68E-03	2.02E-03	2.04E-03	2.23E-03	9.36E-04	4.23E-05	2.10E-03	3.57E-03	2.56E-03
loss_shredding	8.04E-04	1.95E-03	1.07E-03	7.49E-04	2.76E-04	7.80E-04	8.19E-04	1.35E-05	3.90E-04	1.37E-04	5.77E-04	1.60E-04	2.14E-03	4.86E-04	1.92E-03	1.02E-03
mass_total	1.06E-02	4.70E-02	4.61E-02	6.05E-02	5.47E-02	1.17E-01	4.56E-02	6.62E-02	4.72E-02	9.73E-02	4.88E-02	3.73E-03	1.54E-01	6.55E-02	5.52E-02	4.77E-02
non_reusable	1.19E-02	4.70E-02	4.35E-02	5.52E-02	4.68E-02	1.05E-01	4.24E-02	5.77E-02	4.25E-02	8.53E-02	4.45E-02	2.81E-03	1.28E-01	5.87E-02	5.40E-02	4.47E-02
other_fibres_rec	1.83E-03	1.00E-05	1.61E-03	2.31E-03	5.03E-03	9.83E-03	1.05E-03	5.06E-03	1.61E-03	8.17E-03	1.09E-03	3.11E-04	1.75E-02	5.26E-03	8.83E-04	1.99E-03
recovered_fibres_dissolution	4.41E-02	6.73E-02	4.83E-02	4.36E-02	2.28E-02	4.48E-02	4.47E-02	3.04E-02	3.69E-02	3.61E-02	4.12E-02	1.75E-02	8.58E-03	3.52E-02	6.70E-02	4.79E-02
solvent	2.04E-02	2.04E-02	2.04E-02	2.04E-02	2.04E-02	2.04E-02	2.04E-02	2.04E-02	2.04E-02	2.04E-02	2.04E-02	2.04E-02	2.04E-02	2.04E-02	2.04E-02	2.04E-02
solvent_recovery	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00

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