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Market Research on Available Textile Waste Recycling Technologies for Northern Finland, Norway, and Sweden

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Abstract

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This thesis was commissioned research under the THREAD project which aims to explore the circularity of textiles with a focus on reuse and recycling within the Northern Periphery and Arctic (NPA) communities. The necessity of this research stems from the continuously growing amount of textile consumption and waste globally but having inadequate recycling facilities and technologies in place. The Research & Development project managers of Kajaani University of Applied Sciences reached out to International Business students to conduct market research specifically on available textile waste recycling technologies.

With a need to delimit the study, the Northern regions of Finland, Norway, and Sweden were chosen as the areas of focus due to their proximity to one another and their shared demographical and geographical characteristics. There were three research objectives in the study: to identify the currently available textile waste technologies, explore the current textile waste recycling landscape within the public sectors of the regions, and to eventually determine which of the identified technologies would be commercially viable for the areas.

The author reviewed existing literature to establish the research and conceptual background. The Best Available Techniques (BAT) method and the Technology Readiness Level (TRL) were employed to answer the first question. Interviews were conducted to gather primary data from industry experts and a qualitative content analysis was utilized to extract themes and patterns from the responses. Both secondary and primary data were then consolidated to answer the second and third research questions.

The key findings of the research were discussed per research question. Five categories of textile recycling technologies were identified along with their strengths and weaknesses and respective maturity levels. Among these are mechanical, thermal, thermo-mechanical, chemical, and thermo-chemical methods. The current recycling landscape among the regions highlights the challenges the industry faces, the factors to consider when choosing a potentially viable textile waste recycling technology, and the current stance and updates regarding the Extended Producers Responsibility (EPR) on textiles. Based on these data, the author suggests that mechanical recycling technologies would technically be suitable for the areas, but due to numerous considerations, especially the lower-than-average textile waste volume generated per area, it may be recommended to have a shared or centralized recycling facility for these northern regions.

Foreword

I would like to express my gratitude to my thesis commissioning party, Anna, for being patient and supportive of me for the past months and allowing me to work at my own pace. To Tatiana, your input on recycling technologies is instrumental to my learning experience. To the 4 interviewees who shared their time and expertise, thank you for such knowledgeable and eye-opening insights. To my thesis adviser, John, for being critical of my work as you probably believe in me more than I do with myself – I appreciate that.

To my family, friends, and Enhypen, who witnessed and remained understanding of this rollercoaster of a journey, I am grateful to have you, and will spend more time with you all going forward.

It was challenging to conduct market research at this stage as crucial developments are expected to take place within the next years. However, as the research focused on the current textile waste recycling technologies, the existing recycling landscape in the areas, and the ongoing plans regarding the EU directive implementation, as well as the EPR – it is worth having conducted this research and see the developments within the industry.

Conducting research in a field I was entirely unfamiliar with was overwhelming, but the opportunity to contribute to the academe and to the textile waste recycling industry at its early stages feels like a privilege. Most importantly, this research felt extremely rewarding as I personally learned a lot about the circularity of textiles, sustainable practices, and being able to share insights about these with others.

To the readers, thank you for being here, and I hope this research could be of assistance to you. To everyone, may we recognize the consequences of our actions and work towards a more sustainable world with textiles.

Finally, to the greatest author – Lord, thank you, and all glory is Yours.

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List of Key Terminologies & Operational Definitions

Nomenclature of Territorial Units for Statistics (NUTS)

The Nomenclature of Territorial Units for Statistics classification (NUTS) refers to a hierarchical system used to categorize and identify the economic territories of the EU and the UK. It serves various purposes such as collecting and standardizing regional statistics, conducting socio-economic analyses, and framing EU regional policies. The classification includes NUTS 1 for major regions, NUTS 2 for areas relevant to regional policies, and NUTS 3 for smaller, specific regions. (Eurostat, 2021) The northern regions and their codes listed below are identified based on this system.

Northern Regions of Finland

Northern Finland or Pohjois Suomi refer to the three provinces: Finnish Lapland (FID7), Kainuu (FID8), and Northern Ostrobothnia (FID9). All of which are classified under NUTS 3.

Northern Regions of Norway

Northern Norway which is also referred to as Nord-Norge (NO07) includes the counties of Nordland (NO071) and Troms og Finnmark (NO074), both classified as NUTS 3.

Northern Regions of Sweden

Norrland (SE33), the northern region of Sweden, encompasses the counties of Västerbotten (SE331) and Norrbotten (SE332), both falling under the NUTS 3 classification.

Textile

The term textile is broadly used and pertains to various fabrics made from either natural or synthetic materials. (Oelz, 2017) Synthetic and man-made fibers may also refer to the manufacturing process and not just the composition of the material. In this research, clothes or wearing apparel are included in the umbrella term “textile”.

Textile Waste

In this research, the term textile waste would refer to all end-of-life textiles which are textiles discarded by their owners which may or may not be recycled. (Telaketju, 2018)

Textile Waste Recycling

In this research, textile waste recycling, or simply textile recycling refers to either the reuse, recovery, and/or reprocessing of textile materials. The European Parliament and Council of the European Union (2008) do not include energy recovery and reprocessing of textile waste into materials used for fuel under “recycling”. In this research, however, these methods may still be explored under recycling.

Textile Waste Recycling Technologies

To enable recycling, various methods and technologies are required. In this research, textile waste recycling technologies would refer to the different applications of scientific knowledge and discoveries with the use of machinery or equipment, as defined by the Cambridge dictionary.

1 Introduction

This research-based thesis is initiated and commissioned by project managers from the Research & Development department of Kajaani University of Applied Sciences (KAMK), which is a Lead Partner for the THREAD project funded by the Interreg Northern Periphery and Arctic (NPA) Programme. The project managers have reached out to International Business students from KAMK to conduct market research.

This chapter lays down the background of the research, introduces the problem, and enumerates the aim and objectives along with the research questions.

1.1 Research Background

Textiles are fundamental materials in our society due to their wide range of use. In Europe, it is estimated that an average individual purchases 26 kilograms (kg) of textile (European Environment Agency, 2019) and throws away 12 kg of textiles every year. (European Commission, 2023b) Hence, the European Union (EU) set various strategies and regulations for sustainable and circular textiles. Some of these strategies include setting design requirements for producers, restricting the export of textile waste, and incentivizing circular business models. (European Commission, 2022a) This is in line with the 2018 EU directive set that by 2025, EU member states must separately collect at least 50% of textile waste as a measure for high-quality recycling. (Morsen, 2022) There are no fine or penalties in place should a member state fail to adhere to the directive on time. Instead, extended deadlines are provided with respective targets to meet in case these extensions are used. (European Parliament & Council of the European Union, 2018)

One of the most compelling reasons for these plans and actions is because in Europe, textiles rank as the fourth most impactful industry on the environment and contribute significantly to climate change. (European Commission, 2022b) In fact, consumers' improper handling of discarded textiles accounts for approximately 85% of textile waste. (Šajn, 2019) Hence, consumers themselves demand sustainability in the textile industry. (CBI Ministry of Foreign Affairs, 2019)

An approach toward circular textiles involves the management of textile waste, an area that is still in its early stages of research (Heikkilä et al., 2019). As a result, within this study, specific attention will be dedicated to examining this subset of textile waste management – recycling.

1.2 Research Aim, Objectives, and Questions

This study is considered as market research to analyze the current landscape of recycling technologies in the textiles industry. This thesis, as an output, aims to contribute to textile waste management research and development. Specifically, this would contribute to the objectives of the THREAD project which mainly aims to explore the feasibility of textile reuse and recycling for NPA communities. (Belenikhina, 2023) Appendix 1 presents the THREAD project's summary.

Three specific areas from the NPA communities were chosen for this research: Northern Finland, Northern Norway, and Northern Sweden. This is due to the limited duration of the study, the availability of data from the secondary sources and the commissioners, as well as the demographical and geographical similarities of the areas which are of interest. Nonetheless, the research would contribute to the overall aims of the THREAD project.

This research's specific objectives are as follows:

1. Explore the technological readiness level of available textile waste recycling technologies;
2. Investigate the current situation of textile waste recycling within the public sector of Northern Finland, Norway, and Sweden; &
3. Explore and identify commercially viable textile waste recycling technologies for Northern Finland, Norway, and Sweden.

These objectives will be guided by the research questions that correspond to each objective:

1. What technologies are currently available for textile waste recycling?

These technologies will be identified and explored using the Best Available Techniques (BAT) method and will be further assessed via the Technology Readiness Level (TRL) index.

2. What is the present state of textile waste recycling within the public sectors of Northern Finland, Norway, and Sweden?

Aside from existing literature, interviews with industry experts serves as a mean to gather data to answer this research question. This qualitative research method will aid in exploring the current practices, challenges, and potentials of the recycling landscape within the public sectors, specifically, within the municipalities of the areas of focus.

3. Among the identified textile recycling technologies, which exhibits the greatest potential to be commercially viable for Northern Finland, Norway, and Sweden?

This research aims to answer this question after analyzing data gathered from the first two research questions. Subsequently, following the identification of the best available technologies, analysis of their maturity level, and the interviews with the experts, the researcher will analyze all gathered data to provide an answer for this research question.

2 Literature Review

This chapter consists of two main parts. The first section involves a review of the present landscape of the textile recycling industry within the public sector of Northern Finland, Norway, and Sweden. This review would explore facts, reports, and updates pertaining to three geographical areas of focus in this research. The second section is a conceptual framework that lays out textile waste recycling technologies by using the Best Available Techniques (BAT) and the Technology Readiness Level (TRL) scale. This framework serves as an organized structure that unifies the key variables of the research and provides a clear foundation for the study.

2.1 Review of Textile Waste Recycling Landscapes in Northern Finland, Norway, and Sweden's Public Sectors

In section 1.1, the research background established that textile recycling is an integral component of textile waste management, proving its crucial role in the overall effective waste management system. This importance is underscored by various macro-environmental factors, including the European Union's goals and directives, increasing consumer demand for sustainability in textiles, and the escalating environmental impact. These factors collectively emphasize the necessity for further research on this subject.

This section will examine the current state and developments in the textile recycling landscape first in the general Europe and the Nordics, then specifically in Northern Finland, Northern Norway, and Northern Sweden.

2.1.1 General Europe

In July of 2023, it was reported that in the EU, 12.6 million tons of textile waste is generated annually. (Europe Parliament, 2023) As of 2023, approximately 22% of post-consumer textile waste is recycled. (European Commission, 2023a) Further, an estimate of only 1% of the collected waste is recycled fiber-to-fiber (<1%) – which is the process of breaking down a textile item into its component fiber then using this to create a new textile. Another approximate of 10% of which are recycled via other technologies and the remaining “recycled waste” are either reused or exported. (McKinsey & Company, 2022) Annually, the EU exports 1.35-1.85 million metric tons of used textiles, mostly to Asian and African countries. These textiles are either processed locally in Asia for industrial use or re-exported to other African nations after sorting. (Huygens & Caro, 2023) With these numbers, it is apparent that a huge percentage of 65-75% of textile waste is unaccounted for, regardless of if these were collected or not. (McKinsey & Company, 2022) Therefore, the EU aims to improve the sustainability and circularity of textiles not just by recycling textile waste, but by enumerating the key actions that would address several issues in the value chain.

These initiatives include several key actions. Firstly, the introduction of mandatory Ecodesign requirements that aims to extend the life of textile products. Ensuring the high quality of raw materials for textile can increase the durability of the products; further, the mixture or blend of fibers used is observed to ultimately enable the recycling of products as separation of the fiber blends is usually required.

The second key action is the prohibition of the destruction and/or incineration of unsold textiles to encourage responsible production among companies. Third, the issue of microplastic pollution is addressed by focusing on product design, manufacturing processes, as well as on encouraging use of washing machine filters, among others. Fourth, the introduction of a Digital Product Passport for textiles will enable consumers and businesses to be informed about how circular and environmentally friendly the products are and hopefully make more conscious decisions through these.

In relation to this, the fifth key action is the amendment of the Unfair Commercial Practices Directive and Consumer Rights directive which will ensure that consumers will be informed about the durability of the products as well as of relevant repair instructions and repairability scores. Lastly is the proposal of a harmonized Extended Producer Responsibility (EPR) on textile which aims to create a system that encourages collection, sorting, reuse, and recycling of textiles while motivating companies to design products that follow circular economy principles. (European Commission, 2022a)

On July of 2023, proposed amendments to the EU waste rules focused on extending producer responsibility for the textile sector. The scheme outlines that the producer’s responsibility would entail covering the costs associated with collecting textiles, shoes, and textile-related products for re-use or recycling. These schemes are expected to encompass transport, sorting, and support for research and development to enhance the efficiency of sorting and recycling processes. The impact assessment for these proposals, informed by stakeholder consultations and scientific input from the Joint Research Centre, emphasizes the need for concerted action within the textile value chain to prioritize re-use and fiber-to-fiber recycling.

As mentioned in section 1.1, at least a 50% target for separate collection among municipalities is set. However, the legislative proposal leans towards not including a separate collection target, citing variations in collection rates across the EU and to reduce administrative burdens. (Europe Parliament, 2023)

2.1.2 Nordics

In the Nordic countries, there is minimal variation among the textile consumption per person per year, as seen in Table 1 (Fråne et al., 2021). In 2019, it is reported that textile consumption, at least for Finland, has remained consistent for the past 10 years. (East Cham, n.d.) Hence, if the same can be assumed for other Nordic countries, based on these values, it is apparent that textile consumption in the Nordics is significantly lower than the average European consumer's 26kg/year textile consumption.

Type of textiles accounted for	Country	Textile consumption per person/per year (in kg)
Textiles including wearing apparel, furs, leather, and other leather products	Finland	13,5
	Sweden	15
	Norway	22
	Denmark	16

Table 1. Textile Consumption of Nordic countries

Although Nordic countries have a lower textile consumption rate than the general EU, this does not imply that there is no need for action to address textile consumption and waste for these countries. Hence, the Nordic Council of Ministers has mapped the initiatives in the countries to identify the next steps required.

With a focus on collaborative projects from both public and private actors that aim to drive innovation across the entire textile sector towards a more circular approach, 148 projects were mapped. (Munkholm et al., 2023) These projects were categorized among the following: first, materials and design – these projects included those that use locally available, surplus, and recycled materials. As for the designs, issues were addressed by considering recycling, lifetime extension, and resource optimization.

The second category focuses on projects that create local production methods which emphasize customization and digitalization to minimize environmental impact. Through new technologies like AI and cloud services, they aim to enhance competitiveness and facilitate the industry's digital transformation for economically viable, localized production. An example is Sweden’s Mikrofabriker project with Gina Tricot and PaperTale which uses blockchain technology to trace every step of garments’ production. (*The Transparency Project*, n.d.)

The other projects in this category target overproduction by adopting digital, demand-driven production, shifting from "make to sell" to "sell and then make." Digitalizing design and sales processes, including virtual prototyping and 3D-knitting, helps eliminate overproduction and reduce return rates to as low as one percent. Sweden’s 3D Fashion Design Simulation project completed in 2019 which uses 3D modeling for early customer feedback, reducing overproduction in fashion. The system, tested globally, proved user-friendly and successfully eliminated a 3D-modeled sock from a future collection. (*3D Fashion Design Simulation*, 2019)

Focused on sustainability, the next project group aims to minimize water, energy, chemical, and waste impact in dyeing and finishing processes. By developing sustainable dyes, optimizing dyeing methods, and exploring bio-based alternatives, they work to replace synthetic dyes with sources from food, forests, bacteria, and algae, testing for durability and color longevity under varied conditions. In Finland, the BioColour research project creates eco-efficient solutions for producing a diverse range of bio-based dyes and pigments in colors such as yellows, reds, browns, greens, blues, and blacks. (BioColour, 2024)

The third category of the initiatives address the aspects of consumption and circular business models by public procurement which allows public authorities to influence production methods by setting demand standards, showcasing a motivation for active participation in the green transition; emphasis on projects aiming to enable consumer self-repair and implement in-store systems, showcasing the role of information and communication technologies in supporting circularity through digital infrastructure for repairs; take-back and second-hand schemes; and increasing consumer consciousness and demands.

Fourthly, the next initiatives are the focus on this research: collection, sorting, and specifically recycling. The activities here include the collection and production of municipal best practices, exploring and discovering sorting and recycling techniques and technologies, and running of pilot plants and processing facilities.

Lastly, initiatives on stimulating circularity in the textile economy were studied; these include discovery, generation, experimentation, and exchange of tools and knowledge. This research, which is conducted under the THREAD project, may be considered part of this category as it aims to supplement existing knowledge pertaining to the textile circular economy. Consequently, this study serves as additional evidence that there are ongoing actions working to enhance the circularity of textiles in the Nordic region.

In the next sections, available data about the current state of the textile recycling industry in Finland, Norway, and Sweden, and specifically their northern regions, will be explored.

2.1.3 Northen Finland

The government of Finland states that the country's goal is to become a carbon-neutral circular society by 2035, and carbon negative after that. Thereby strengthening its commitment to reforming climate policies and ensuring that actions are in place to achieve this goal. (Department of Economic and Social Affairs, 2019) The EU waste directive mandates that the collection and segregation of textile should be started by 2025, but as a potential forerunner, Finland has officially started this movement at the start of 2023. Local networks have set up textile collecting and sorting facilities.(European Commission, 2022a)

In an interview with Emppu Nurminen, the sorting instructor and head of the vintage department at Nextiili Ry, a recycling association which takes part in the pilot textile collection, he explains that as this practice is continuously executed, the amount of textile waste collected and the types of textile waste, specifically, mixed, and contaminated ones, make the need for recycling technologies more apparent. (Zhuravleva & Nurminen, 2021)

Since 2021, two companies have trailblazed the textile waste recycling movement and invested in end-of-life textile refinement facilities: Rester Oy and Lounais-Suomen Jätehuolto (LSJH). These are located in the Green Field Hub in Paimio in Southwestern Finland. Rester Oy processes end-of-life textiles from businesses while LSJH creates local solutions for households. (Association for Finnish Work, 2020) In August of 2023, LSJH is known to be selling its plant to Rester Oy. (*Rester Oy Buys LSJH's Pilot Line for End-of-Life Textile Fibre Opening*, 2023)

Currently, LSJH, in cooperation with local municipalities around Finland, are developing a national end-of-life textile collection network. Pre-sorting is and should be completed before sending the collected textile to LSJH's refinement facilities. This helps avoid the unnecessary transport of textiles that are beyond recycling. (Lounais-Suomen Jätehuolto, n.d.-a) In 2022, 741 tons of textile have been received and treated nationally, among which, 300 tons of sorted textile materials have been sold. (Pokela, 2023)

Simultaneously, LSJH is also planning to build what is supposed to be the Northern Europe's largest end-of-life textile recycling plant in Topinpuisto, Turku, Finland. However, its implementation is put on hold as discussions on Extended Producer Responsibility (EPR) continuously arise. (Saarinen, 2023) According to the OECD, EPR is a market-based tool that extends the manufacturer's responsibilities to all stages of the textile's life cycle, particularly the collection, sorting, recycling, and final disposal. EPR aims to encourage overall environmental enhancements throughout the life cycle of product systems. The associated financial commitment manifests itself as a fee included into the product's market price. (European Union, 2021)

At the time of writing, there has been no decision yet regarding EPR. If the directive is implemented, there might not be a need for the large-scale end-of-life textile recycling plant as producers or companies may opt to manage their textile waste by sending them to countries that are willing to take these with the cheapest fees. In practice, these countries may be from Asia or Africa, which then act like dumpsites for textile waste. This possibility may wreck years of effort and research on waste management for textiles in Finland. (Saarinen, 2023)

Furthermore, based on the THREAD project's collected data (2023), Kiertokaari Oy, a waste management company which offers services to the northern regions (Kiertokaari Oy, 2023), reports that there were ~91,000 kilograms of textile waste collected within 6 months for North Ostrobothnia and Lapland. By the end of the year, 201,372 kilograms of textile waste for the same areas have been collected which implies that more than 110,300 kilograms added for the second half of 2023.

For the Kainuu region, Entrinki, a specialist recycling facility (Entrinki, 2023), reports ~26,300 kilograms of textile waste collected within the first 6 months of 2023. Further, it is estimated that there is approximately 0,4 – 1 kilogram of textile waste per inhabitant in the region. According to the data from the THREAD project (2023), an estimate of 4-11 kilograms of textile waste is generated per inhabitant in 2021. The population in the northern provinces already account for around 12% of the entire Finnish's 5.5 million population. (*Population and Society*, 2023) Hence, for a considerably large share in the national population, the estimated volume of textile waste collected per capita is comparably low than that of the average Finnish inhabitant.

2.1.4 Northern Norway

In Table 1, the textile consumption volume per capita for Norway stands out in comparison with other Nordic countries. The report states that in its original source, a wider scope of textile was used for Norway, hence, the value may not be directly comparable to that of others.

In 2019, Nord-norge constitutes about 9% of the entire Norwegian population (AdminStat, 2019), which may be similar to that of Finland's, as it has a smaller national population. Furthermore, the country has not also implemented EPR yet, but the clothing research group at Consumption Research Norway (SIFO) expresses their support for the EPR scheme. (Klepp et al., 2022)

According to the Nordic Council of Ministers (2023), Miljødirektoratet or the Norwegian Environment Agency recommends the implementation of the separate textile waste collection to start in 2025 which follows EU's mandates. Currently, charities and private companies volunteer to collect reusable textile waste. Further, some municipalities have been collecting via a drop-off scheme both reusable and waste textiles for recycling. Nonetheless, Miljødirektoratet allows municipalities to decide between a pick-up or drop-off scheme to collect textile waste. To date, there is no reported volume of textile waste collected as there are no national procedures in place yet.

2.1.5 Northern Sweden

Comparably with northern Finland's, Norrland's population also constitutes to approximately 12% of the country's population. (*Norrland*, n.d.) In Table 1 above, Sweden's estimated textile consumption per person per year does not appear immensely larger than Finland's – considering its national population to be almost twice that of Finland. As for textile waste recycling, only 5% of collected waste is reported to be recycled. (*Siptex - Textile Sorting*, n.d.)

Since 2021, there are various sources indicating that Sweden will be implementing the EPR by January of 2022, although companies and Producer Responsibility Organizations' (PROs) obligations would primarily start in January of 2024. (Glover, 2020) As explained above, this would mean extended textile waste management responsibilities for producers and private companies. Hence, a large-scale recycling facility that would need expansive recycling technologies would not be essential. Still, the need for feasible and appropriate recycling technologies remains and could still provide substantial information for those responsible for textile waste management, on either a larger or smaller scale.

Similarly based on the Nordic Council of Ministers (2023), it explains that the EPR has been suggested but the implementation was on hold at the time of writing. As for waste and reusable textile collections, there are municipalities who already collect and sort and there are also charities and private companies who collect reusable textiles in a separate stream. Therefore, no official data has been reported yet regarding the volume of textile waste collected.

2.1.6 Mutual Needs

Although these areas are known to have sparse populations, as seen above, the population within the northern regions of Finland, Sweden, and Norway varies. Without the secondary data on Norr-land and Nord-Norge's textile waste volume, it may seem unclear why these regions are chosen for this research, aside from their proximity. To put it simply, these areas are of interest due to their biggest commonality – geographical conditions that are mostly characterized by the Arctic climate which commonly has long and extreme winters.

The most apparent effect of these areas' similar geographical conditions – specifically weather – is that textiles, especially clothing, that inhabitants dispose of may have similar compositions. It is also essential to remember that textile waste recycling relies on initial stages or processes such as waste collection, sorting, and delivery to recycling facilities. The Life Cycle Assessment (LCA) lists and defines the different measures of products or services' environmental impacts. (*Life Cycle Assessment (LCA)*, n.d.) In this case, the processes that lead to textile waste recycling contribute further to its negative environmental impacts, which may also be caused by the areas' geographical conditions. Possibly the biggest impact would be the need for specialized equipment and additional materials that deplete natural resources faster.

In a business perspective, these specialized assets would mean greater costs. Harsh weather conditions such as extreme winters in these areas would entail the need for heating systems in waste collection, sorting, and recycling facilities; may impact quality of textiles that can lead to faster degradation; and overall impacts the type/s of technologies to be adopted in these areas.

Furthermore, according to McKinsey and Company (2022), generally, the European textile recycling industry would require 6-7 billion EUR to invest in collection sites, sorting, and recycling facilities. Based on their analysis, profit would be generated for every step of the value chain, if recycled products have the same quality as virgin materials. However, this investment decision remains unclear due to the proposal of the EPR which will affect the entire textile waste management industry.

Hence, as this research progresses, further developments and updates on the industry will be included. Nonetheless, as there is an apparent need to identify suitable and commercially viable textile waste recycling technologies specifically in the areas of interest, the research continues.

2.2 Conceptual Framework

A conceptual framework illustrates the variables used in research and maps out how they interconnect to form cohesive conclusions. (Jabareen, 2009)). In this research, the framework outlines the variables which are the textile waste recycling technologies, employing the Best Available Techniques (BAT) method and the Technology Readiness Level (TRL) scale. The BAT will serve as a representation of the technological solutions available for textile waste recycling, and the TRL will serve as a scale of measurement to evaluate the development stages of the technologies. Together, this framework can help determine the suitability of different technologies based on their readiness levels and effectiveness in addressing specific challenges or goals.

2.2.1 Best Available Techniques

Due to the broad and diverse nature of textiles, it is only logical that there are also various technologies to recycle textile waste. In this section, the Best Available Techniques (BAT) method will be utilized. Technically, the BAT refers to the latest stage of certain processes, methods, or technologies that are suitable for limiting emissions or waste. (Logan et al., 2013) In this case, another criteria would be those technologies that are already or have the potential to be commercialized. These BAT would be laid out, categorized, and defined along with their strengths and weaknesses.

There are numerous textile recycling methods, techniques, and technologies available – they may currently be developed in labs, used in pilot-scale plants, or even used commercially. These may include upcycling textile waste, using them as insulation materials, filling materials, or even utilizing extracted fibers as concrete reinforcement or generally for green building materials.

As mentioned in section 2.1.1, less than 1% of collected textile waste is recycled from fiber-to-fiber (F2F) technologies. This recycling method holds great promise to aid in the circularity of textiles as it keeps the resources in circulation instead of allowing these to go to waste or to be used in other sectors.

In addition, according to McKinsey & Company (2022), fiber-to-fiber technologies are considered the most sustainable recycling methods. This is because it allows textile waste to be recycled without needing chemical-altering technologies, hence, it suggests a lower cost. However, F2F is still under-utilized. Although continuous research and development are in place, some barriers to this method include the blend or mixture of various fibers in textiles which current technologies cannot handle and the need to have zippers and buttons removed from clothing to process them for F2F recycling. Further, most F2F technologies require strict fiber composition and purity.

Therefore, and nonetheless, in this research, the focus would be on the best available technologies that enable fiber-to-fiber recycling. Recycling categories to be included are mechanical, thermal, thermo-mechanical, chemical, and thermo-chemical. Table 2 and 3 in the end summarizes the data from this section.

Mechanical Recycling

Mechanical recycling is one of the primary methods used to recycle textile waste. It involves various processes such as shredding, sorting, and fiber production. These processes aim to transform textile waste into reusable materials, reducing the environmental impact of the textile industry. (Saha, 2020)

In addition, mechanical recycling refers to the use of physical methods to convert textile waste into recycled usable fibers. Since there are no composition-altering chemicals or techniques used for this method, the fiber composition of the textile waste will remain to be the composition of the recycled fiber. The fiber types that are suitable for this method are cotton, polyester, mono-fiber fabrics, and polycotton blends. (Girn et al., 2019)

Under this method, there are subcategories called “open-loop” or “closed-loop” recycling. (McKinsey & Company, 2022) Open-loop recycling is what is commonly perceived as “downcycling”. It involves converting the textile waste into new products different from their different form or usage. For instance, old clothing may be converted into insulation materials or wiping rags. The fiber composition of the material remains, but the product may have a lower quality, functionality, or value. This then poses a threat or challenge to keeping the materials or the resources “on the loop”. That is how the concept of fiber blending helps. By mixing other recycled fibers together, higher quality may be obtained.

The first step in open-loop mechanical recycling is shredding. This process involves breaking down textile waste into smaller pieces, making it easier to handle and process these further. Shredding can be done using different techniques, such as mechanical shearing or cutting, depending on the type of textile waste being recycled.

After shredding, the next crucial step is sorting. This process involves separating the shredded textile waste based on its composition, color, and other characteristics. Sorting ensures that the recycled materials are of high quality and suitable for further processing. Advanced technologies, such as optical sorting systems, are often used to automate this process and improve efficiency.

Once the textile waste has been shredded and sorted, it can be transformed into new fibers. Fiber production typically involves either mechanical or chemical processes. In mechanical fiber production, shredded waste is mechanically processed to create fibers that can be used in various textile applications. This process is commonly known as fiber regeneration. (Saha, 2020)

One Austrian recycling company, **ANDRITZ**, have produced a technology called ADuro shredders, that enables textile fiber preparation. It allows processes such as shredding and removing impurities such as zippers and ornaments, which would be of great help not just to mechanical recycling methods but to other technologies as well. This technology can handle up to 200 tons of textile per day and ensures up to 95% purity of the output material. Further, this technology is utilized by Renewcell for its Sundsvall recycling plant. (Andritz, n.d.)

In Finland, **LSJH** is known to be utilizing open-loop mechanical methods in recycling post-consumer textile waste at their Paimio plant. It reports to use the technology to open back fibers which refers to the description of mechanical recycling of mechanically separating and extracting fibers to enable their reuse in creating new textiles.

The pilot plant has been operating since 2021 and it aims to have the capacity to process 15,000 tons of textiles annually by 2025. (Pokela, 2023) The entire facility was made possible by approximately EUR21-22 million investment, with the share of the circular economy investment grant to be at around EUR5.2 million. (Lounais-Suomen Jätehuolto, n.d.-b) However, as also mentioned in section 2.1.3, LSJH has been bought by Rester Oy and will assume its administration by 2024. (*Rester Oy Buys LSJH's Pilot Line for End-of-Life Textile Fibre Opening*, 2023) This is only worth mentioning as this may open questions regarding the specific capacity goals of the plant.

Nevertheless, the extracted fibers serve as raw materials for producing various new products, including threads, different non-woven fabrics, insulation materials, fillings, acoustic panels, filter fabrics, and composite materials. Further, all municipalities in Finland with their respective waste management companies can deliver their post-consumer textile waste to the plant for processing. Similarly, businesses or companies may also reach out to LSJH or Rester Oy if they are interested in using the recycled materials to produce their own products. (Lounais-Suomen Jätehuolto, n.d.-b)

On the other hand, the closed-loop recycling process aims to maintain the value of the original material by recycling textile waste into new textiles or products of similar quality. The process involves breaking down used textiles into their components then creating new textiles or garments. It strives to keep the resources "on the loop" without significant loss of quality, reducing the need for new raw materials and minimizing waste. Chemical methods may be required to enable this. (McKinsey & Company, 2022)

Recover™ provides end-to-end closed-loop solutions which converts cotton and polyester blends from textile waste into high quality recycled cotton fibers and fiber blends. To enable this, the company utilizes their own private machine optimization formula. (Poratelli, 2022)

Thermal Recycling

Thermal recycling refers to the melting process of textile waste to be used for F2F recycling. (Heikkilä et al., 2019) Based on its name, it involves processes that use heat to break down textile fibers without altering their fundamental chemical composition. The method aims to regenerate or modify the original fibers for reuse in new textile products.

Although not directly considered as a recycling method, melt spinning deals with recycled materials from various technologies to create new fibers. (*Textile Waste - a Problem*, n.d.) The **Research Institute of Sweden (RISE)** has established a pilot-scale multi-component melt spinning equipment in their facility. It is commonly used to produce synthetic textile fibers. In the process of melt spinning, a heated thermoplastic polymer turns into a liquid, which is then pushed through a specialized opening and stretched out to create thin threads or fibers. RISE has various machines for making fibers, from small-scale equipment for testing new materials' spinning ability using 10g mono-filament extrusion, to larger lab and pilot-scale melt spinning machines producing between 0.1 and 6 kg/h. (Lund, n.d.)

Melt spinning's strengths are its fast and efficient method, with speeds ranging from 2500 to 3000 feet per minute, resulting in increased productivity and its low initial investment requirement, making it economically viable. However, its main disadvantage is that it is only suitable for synthetic materials. Also, it demands a high input of heat and requires constant temperature control for optimal results. (*Melt Spinning Process | Advantages and Disadvantages of Melt Spinning*, 2017)

Thermo-mechanical Recycling

Above, mechanical, and thermal recycling methods were explained. Another recycling method that holds potential for commercialization is called the thermo-mechanical method, which incorporates the concepts of the earlier stated processes. Hence, thermo-mechanical methods require the combination of mechanical pressure and heat. This technology is commonly used for synthetic textiles such as polyester and polyamide. However, it cannot be used for natural fibers like cotton or wool. This is because of the significant differences between synthetic fibers and natural fibers' composition, structure, and reaction to high temperatures.

This method targets only high-purity fibers. It requires a 99% purity of polyester and polyamide and is unable to process elastane and its output are polymers. Despite this strict requirement on its feedstock, this technology is included in the BAT as there is a company utilizing this technology commercially. (McKinsey & Company, 2022)

EarthProtex is a technology innovation company which focuses on using waste as resources and creating products for the circular economy. They currently have three platforms utilizing different technologies for different goals: Tex2Tex™, Agrefinery™, and Upspun™.

Currently, their technology called Tex2Tex™ utilizes a thermo-mechanical approach in recycling polyester. Its technology is described as high-capacity, cost-competitive, scalable, and low-impact. The Tex2tex™ thermo-mechanical technology enhances the intrinsic viscosity of the material and eliminates impurities using advanced filtration and produces Tex2tex™ fiber which is then spun into filament yarn. It is also known to be able to produce 50,000 tons of fiber annually. (Tex2Tex, n.d.)

Chemical Recycling

Chemical recycling is defined as the involvement of chemical processes or materials in breaking down textile into its raw materials. There are various technologies that exemplify this, but these may be generally categorized into two: chemical recycling in polymeric and monomeric level.

Chemical recycling at the polymeric level refers to dissolving or breaking down textile waste to their original polymer forms. For cotton and manmade cellulosic fiber (MMCF), a pulping process may be employed to create MMCF such as viscose, lyocell, or modal, or simply generate the existing MMCF. (McKinsey & Company, 2022) Further, the quality of the new product is the same as the original counterpart. (Heikkilä et al., 2019)

Another technology to recycle polyester and polycotton fiber are solvent-based methods which include filtration to extract polymers and are aimed at breaking down these textiles back to their original polymer form, such as polyethylene terephthalate (PET) for polyester. (McKinsey & Company, 2022)

Renewcell in Sweden utilizes dissolution or pulping technology to recycle textile waste to produce Circulose ™. Their method is to turn prepared textile waste into “slurry”, take away contaminants such as polyester, and the slurry would be dried up to produce sheets to be sent off to fiber producers. (CIRCULOSE, 2023) The initial demo plant was able to produce 7,000 tons of biodegradable pulp each year. In 2021, an investment of EUR30.75 million was lent by the European Investment Bank for Renewcell to build its first commercial-scale plant in Sundsvall. This plant now has the capacity to produce 60,000 tons of pulp each year.

An example of a solvent-based method is used by **Worn Again technologies** in Switzerland, which relies on changing solvents or temperatures to dissolve dyes first, leaving the PET unaffected. The initial solvent swells but does not dissolve PET under specific conditions. For example, dyes dissolve in ethyl benzoate at 120°C, separating from the plastic. Then, after removing the dye solution, a new batch of ethyl benzoate at 180°C dissolves the polymer, removing any impurities that did initially not dissolve. To make it cost-effective, the solvent needs recycling, and the process simplifies this by using the same solvent repeatedly. Achieving a 96% PET recovery rate is considered satisfactory for this method to be economically feasible. (Sherwood, 2020) However, solvent selection is crucial for this method as different types of fibers may require different solvents. Also, ensuring zero to limited damage or fiber quality reduction is crucial.

Alternatively, textile waste may be chemically recycled at the monomer level. This method is commonly used to recycle polyester and polyamide. There are contrasting viewpoints regarding whether depolymerization is a polymeric or monomeric-level method, but according to both McKinsey's and Telaketju's reports, it is a method to break down polymer chains into monomers which are then used for the repolymerization of polymers or used as a resource for other materials.

There are also various methods for depolymerization such as glycolysis which uses ethylene glycol and methanolysis which uses methanol, both of which are executed under pressure and at 200°C. Other methods are hydrolysis techniques which use water plus a corresponding acid base and an enzymatic method to depolymerize. (McKinsey & Company, 2022)

Glycolysis is reported to require only low energy consumption but can be a slow process if a catalyst is not used. (Damayanti et al., 2021) Some catalyst options may be enzymes and alkaline or metal-based catalysts which accelerate the reaction rate and enhance the efficiency of polymer degradation. According to McKinsey (2020), this method is considered costly as it would require a high capital investment due to the need of adding the polymerization step.

For hydrolysis, enzymatic hydrolysis may be taken into consideration. For this process, pretreatment is essential to remove unwanted contaminants. Cotton is found to be a suitable feedstock for the process to produce cellulosic ethanol, which may be used as biofuel or a general source of energy for the value chain. Nonetheless, some concerns in the process include the need for large amounts of water and energy for the process. (Piribauer & Bartl, 2019) Other hydrolysis processes are also studied by using acid and alkaline and testing on other cellulose-rich materials, but most of these are only experimented and used in the laboratory setting for now.

Although most chemical recycling methods currently only exist in labs and pilot scale experiments, one company, **Eastman**, is known to utilize methanolysis on their textile recycling technology.

Eastman is a global specialty materials company in the US that focuses on developing groundbreaking technologies and produce sustainable materials. In February 2021, they announced a USD250 million investment to build a methanolysis plant in Tennessee. The plant aims to process 100,000 metric tons of textile waste, specifically polyster. One of the biggest advantages of their technology is that it produces rDMT or recycled Dimethyl Terephthalate, which is used in the production of PET, which has a 29% lower carbon-footprint than when using conventional methods. (Granados et al., 2022) Although it is difficult to say whether the investment cost is high based on the technology and the capacity, McKinsey (2020) reports that along with glycolysis, methanolysis requires a higher investment due to these needing extra repolymerization technologies or processes incorporated.

In addition, **Infinited Fiber** in Finland appears to be utilizing depolymerization technologies in creating cellulose carbamate fiber or simply Infinna™, a recycled and regenerated fiber that is from broken down textiles to their polymer level;. As of 2023, Infinited Fiber is aiming to open its flagship factory in at least 2 years' time and have a production capacity of 30,000 tons. Generally, the company's planned investment is around EUR400 million for its factory in Kemi. (*Infinited Fiber´s Flagship Factory Progresses*, 2023)

Thermo-chemical Recycling

Thermo-chemical recycling, or the gasification of materials, refers to processes that often involve a combination of thermal and chemical treatments to break down textile waste into its constituent components, which can then be utilized to create new fibers or materials. (McKinsey & Company, 2022) Although thermo-chemical recycling techniques do not directly produce fibers, these methods produce syngas that has the potential to substitute fossil-based resources across various value chains, including the manufacturing of synthetic fibers.

This category comes with 2 main benefits to the recycling industry. First, it has no restrictions on the textile type, fiber composition and purity, as well as if the textile waste is dirty or contaminated. Second, it can treat and recycle other waste from the value chain such as residual waste in the production of MMCF, and non-textile waste generated from other processes that would otherwise just be incinerated or disposed in landfills. (McKinsey & Company, 2022)

In essence, thermo-chemical recycling methods show promise in addressing 100% of textile waste, residual waste from various recycling processes, parts of waste streams currently managed through incineration, and even non-textile waste, likely offering a more comprehensive and sustainable approach to managing diverse types of waste materials.

An example of a technology under this method is pyrolysis which is the process of decomposing synthetic materials at high temperatures in the absence of oxygen, which can then produce fuel, gases, or solid residues. It can process multi-material textiles which are either sorted or not, hence it minimizes the preparation time and cost for waste. (Piribauer & Bartl, 2019) The weakness of this high-temperature reaction process is that it requires high energy consumption which would also be costly. (Damayanti et al., 2021).

As the technology does not directly produce fiber outputs, the products need to undergo further processing in earlier refining and petrochemical procedures. However, the intricate process of breaking them down into molecular components demands substantial investment. The primary materials produced need extensive refinement, potentially leading to increased processing expenses and a larger environmental impact in terms of carbon emissions. (McKinsey & Company, 2022)

Not much information is available regarding whether thermo-chemical methods are utilized commercially, but there are numerous research and experiments regarding the technology. An example is the construction of a pilot pyrolysis plant in Lithuania by **the Kaunas University of Technology** and their energy institute. The team of scientists' focus is on recycling lint micro-fiber and they were able to produce oil, gas, and char from the experiments. (Kaunas University of Technology, 2021) The report does not indicate the capacity of the pilot plant, the amount of collected microfiber used, nor the temperature used by their pyrolysis process. However, in another report, it states that the main pyrolysis stage occurs at around 300-380 degrees Celsius. (Miranda et al., 2007)

Another recycling technology which has contrasting opinions about is Hydrothermal Liquefaction or HTL. McKinsey (2020) states that hydrothermal processes are under polymeric-level chemical technologies, however, another report describes HTL as a thermo-chemical method (Matayeva & Biller, 2022). In this research, HTL will be categorized under thermo-chemical recycling as most hydrothermal processes rely not only on chemical reactions but also on heat-driven processes.

Nevertheless, HTL is a thermo-chemical method which produces liquid fuel from synthetic and biopolymers. In 2022, researchers on a pilot-scale HTL research in Denmark tested the process under 300-400 degrees Celsius for mixed textiles. It was found that as the temperature rose, there was a gradual increase in gas and oil yields, accompanied by a corresponding decrease in solid yield. Specifically, bio-oil obtained from the continuous process was refined at 400 degrees with the use of sulfided CoMo (Cobalt plus Molybdenum) and NiMo (Nickel and Molybdenum) catalysts. (Anastasakis et al., 2018) Hence confirming the main advantage of the method which does not require preparations such as sorting and purification of wastes and mixed textiles. (Matayeva & Biller, 2022)

Recycling technology	**Description**	**Textile Type**	**Strengths**	**Weaknesses**
Mechanical	Physical processing of textile to create new products/materials without altering chemical structure			
Open-loop	Also known as "downcycling"	Cotton, polyester, mono-fiber fabrics, poly-cotton blends	Commercially proven Low energy Cost-efficient	Quality degradation
Closed-loop	Aims to maintain virgin quality			Strict requirement on feedstock purity and composition
Thermal	Breaking down textile by melt spinning	Synthetic textiles	High production speed Does not require special chemicals	Requires high temperature and constant monitoring
Thermo-mechanical	Combination of mechanical pressure and heat	Synthetic textiles such as Polyester and Polyamide	Commercially used High-capacity	Strict requirement on feedstock purity and composition

			Cost-competitive Low impact	Cannot be used for natural fibers
Chemical	The involvement of chemical processes or materials in breaking down textile into its raw materials			
Polymer-level	Breaking down textile waste into their fundamental polymer components			
Pulping	Turning waste into “slurry”	Cotton and MMCF	Able to maintain the quality of the original material	Limited material capability
Solvent-based	Use of solvent and filtration	Polyester and polycotton fiber	Potentially low-cost	Sensitive solvent selection
Monomer-level	Break down polymer chains into monomers for repolymerization			
Depolymerization	Process of dissolving the textile into a solvent form	Synthetic polymers	Commercially used	Does not allow contaminated, white, and dark shade fabrics
Glycolysis	Use of ethylene glycol	Polyester-based materials	Low energy	Slow process High capital investment

Methanolysis	Use of methanol	PET-based materials	Commercially used with years of research	High capital investment
Hydrolysis	Use of water and acid or enzyme	Natural fibers	Can handle wide range of natural fibers	Uses large amounts of water and energy
Thermo-chemical	Combination of thermal and chemical treatments to break down textile waste into its constituent components			
Pyrolysis	Decomposing organic materials at high temperatures in the absence of oxygen	Synthetic fibers; blended fibers	Wide range of materials to recycle	Energy intensive
Hydrothermal Liquefaction	Break down waste under high temperature and pressure of water or solvent	Synthetic and biopolymers	Does not require pretreatment	Energy intensive

Table 2. BAT Summary

Recycling technology	Example	Recycled Product	Capacity	Total investment cost
Mechanical	LSJH, Paimio, Finland	Recycled fibers	Recycle 15,000 tons/annually by 2025	EUR21-22 million
Thermal	Melt spinning equipment – RISE, Sweden	Synthetic fibers	Produce 6kg/hour max	Varies
Thermo-mechanical	Tex2Tex™, US	Tex2tex™ fiber; filament yarn	Produce 50,000 tons annually	Data unavailable
Chemical **Polymer-level**	Pulping – Renewcell, Sweden Pulping – Infinited Fiber, Finland Solvent-based – Worn Again, UK	Circulose™ Infinna™ Recycled fibers	Produce 60,000 tons annually For 2025 facility – produce 30,000 tons annually For 2024 facility – recycle 1000 tons annually	EUR 30.75 million For 2025 facility – EUR220 million For 2024 facility – EUR31.4 million
Monomer-level	Eastman, US	Recycled Dimethyl Terephthalate (rDMT)	Recycle 100,000 tons annually	USD250 million
Thermo-chemical	Pyrolysis – pilot-scale, Lithuania	Oil, gas, char	Data unavailable	Data unavailable

	HTL – pilot-scale, Denmark	Viscous oil	Feed capacity – 100 liters/hour	Data unavaila-ble

Table 3. BAT Application Examples

2.2.2 Technology Readiness Level

The Technology Readiness Level (TRL) scale serves as a benchmarking tool for evaluating the advancement of a specific technology from its initial planning phase (TRL 1) to its complete and full-range demonstration (TRL 9). (Australian Renewable Energy Agency, n.d.) This tool was originally coined and used by NASA to assess the maturity of a technical product. In the EU, the TRL was first used in 2014 to aid in assessing applications for funding. (Durm, 2023) The EU commission has since then modified the definition of the TRL for its funding instruments. Figure 1 shows the structure of the EU Commission's TRL index. (*What Are the Technology Readiness Levels (TRL)?*, n.d.)

This tool serves as a systematic way to gauge technological maturity to make informed decisions about their suitability for the areas in question. Furthermore, a technology's readiness is essential to determine whether it is ready for commercialization. Technologies with a higher TRL are more likely to have undergone all necessary compliance checks and would be expected to meet the demands of its appropriate market and users.

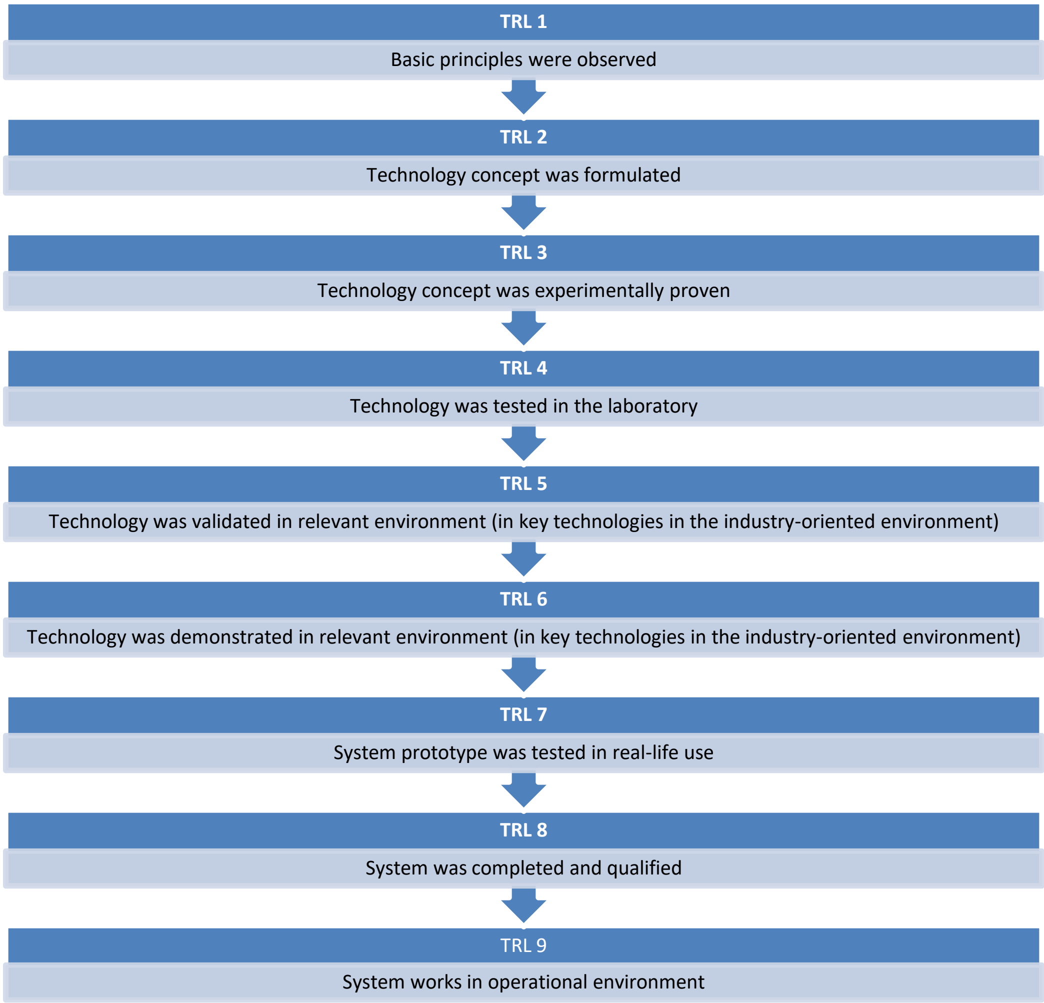

Figure 1. Technology Readiness Level Index

In this section, the technology readiness of the five categories of textile recycling technologies included in the BAT from section 2.2.1 will be analyzed using the TRL scale. It is crucial to note that the assessment here is limited to specific examples and cases only. The assessed TRL of the given examples may not reflect the full spectrum of the technologies' readiness across all possible uses. Other unexplored companies and organizations or other industries may be utilizing the same technologies with a varied TRL.

Table 4 in the end summarizes the TRL of the technologies included in the BAT.

Mechanical Recycling

In Finland, LSJH adapts the use of mechanical technologies at their plant in Paimio. Currently, its capacity can process up to 5 million kilograms of textiles annually. (Garton, n.d.)

Based on the EU Commission's TRL guide, the commercial use of mechanical recycling would imply that its TRL is at the least above 7. It may be between 8-9 as the technology has been completed and is used in an operational environment. However, as gleaned from section 2.2.1, there are still challenges regarding the strength and quality of the produced recycled fibers which would entail further development of the technology.

Specifically for mechanical F2F methods, in 2016, it was reported the economic viability is unlikely due to the low fiber quality of recycled products. (Ljungkvist, 2016) However, years later, Telaketju (2020) already reports the use of mechanical F2F in various stages – pilot, operational, and commercial – which may justify the TRL of 8-9.

Thermal Recycling

Thermal recycling is a promising approach for tackling textile waste, utilizing high temperatures to break down the waste and extract valuable resources. In the section above, melt spinning was given as an example.

Although the method is not exactly a "direct recycling" method as it is a process of turning recycling materials into new products, the readiness level of this technology may be assessed at 6. This level shows that the technology is demonstrated in a relevant operational environment but may not be ready for real-life conditions and capacity yet. The basis for this would be the pilot-scale melt spinning equipment established by RISE which is also continuously tested in the lab.

Thermo-mechanical Recycling

Thermo-mechanical recycling is a promising method for recycling textile waste that combines the principles of both thermal and mechanical processes. By subjecting the waste materials to heat and mechanical forces, this method aims to break down the complex structures of the textiles and recover valuable materials for reuse.

Similarly with the mechanical method, this technology is used commercially by EarthProtex to produce Tex2Tex fiber. Thus, it can be concluded that the technology's readiness level may be at 8-9. However, because of the strict feedstock requirements for this technology, it is still underutilized and continuously developing.

Chemical Recycling

Chemical recycling is another promising method for tackling textile waste as it involves breaking down the polymers in the waste materials and converting them into useful chemical compounds or monomers that can be used to produce new textiles or other products. This process not only helps in reducing waste but also contributes to the conservation of resources. The technologies were subdivided into those which break down waste to polymer or monomer level.

Technologies which break down waste to their polymeric level include dissolution or pulping, and solvent-based methods. As for the monomeric level, technologies include depolymerization processes such as glycolysis, methanolysis, and hydrolysis.

Dissolution or pulping methods are utilized commercially by Renewcell which would imply a higher TRL of 8-9. The same can be implied for solvent-based recycling, which is commercially used by Worn Again technologies.

For technologies enabling monomeric level processes, generally, depolymerization is utilized commercially by Infinited Fiber to produce Infinna. It is unsure which exact depolymerization technique is used, but this commercial use shows much promise and development to the technology. Therefore, for this case, it can suggest that the TRL is at 8-9.

Although there is currently no commercial use of glycolysis for textile recycling, numerous research is conducted to learn more about and develop the process. In fact, it is described as a highly promising recycling method due to its low cost and low energy consumption. (Guo et al., 2021) This would bring its TRL to a 4 as it is validated only in a lab environment.

Methanolysis is known to be utilized by a company called Eastman which reports usage of the method which they planned as early as 2010s but the market “was not ready for it”. Therefore, this could imply that the TRl for methanolysis is at 8-9 now.

For hydrolysis, according to Piribauer and Bartl (2019), the technology is not feasible with polyester as the process takes months and may be difficult to consider as economically viable. Therefore, hydrolysis may be at TRL 4 as the technology has only been utilized in a laboratory setting.

Thermo-chemical Recycling

Thermo-chemical recycling, although not an F2F method, shows promise in tackling the challenges associated with various waste in the general value chain.

Pyrolysis is already utilized by companies who recycle plastic waste hence its TRL in that context will be higher. In the textile waste recycling industry, the TRL of pyrolysis technologies may be between 6-7. The technology demonstrated success in not just waste-to-energy processes, but also recovered nylon monomers from textile waste containing nylon. Still, continuous research and experiments are conducted to further utilize this highly promising method.

As for HTL, based on the example, its TRL may currently be at 6-7 as the technology is demonstrated in an operational environment, in that case, a pilot-lab in Denmark.

Technology	**Technology Readiness Level**	**Justification based on example**
Mechanical	8-9	Commercially used (LSJH, Finland)
Thermal	6-7	Pilot-scale use (RISE, Sweden)
Thermo-mechanical	8-9	Commercially used (EarthProtex, US)
Chemical		
Polymer-level		
Dissolution/ Pulping	8-9	Commercially used (Renewcell, Sweden)
Solvent-based	8-9	Commercially used (Worn Again, UK)
Monomer-level		
Depolymerization	8-9	Commercially used (Infinited Fiber, Finland)
Glycolysis	4	Laboratory-scale use
Methanolysis	8-9	Commercially used (Eastman, US)

Hydrolysis	4	Laboratory-scale use
Thermo-chemical Pyrolysis Hydrothermal Liquefaction	 6-7 6-7	 Demonstrated in relevant environment Pilot-scale use (Denmark)

Table 4. Technology Readiness Level Assessment Summary

As gleaned from the table, the different technologies also have varying degrees of maturity. Despite the textile recycling industry being fairly in its early stages, advancements are evident with commercially used and continuously evolving technologies employed across numerous countries.

Incorporating the Best Available Techniques (BAT) and the Technology Readiness Level scale into the conceptual framework provides a foundation for the subsequent parts of the research. Combining these methods ensures a more holistic evaluation of technologies. It considers their effectiveness in meeting the defined standards and their preparedness for widespread commercial use (TRL), providing a more robust foundation for decision-making.

3 Methodology

This chapter provides information regarding the research design which includes the data sources and collection processes, the data analysis, and the general research procedure. Thereafter, reliability, validity, and ethical issues are addressed.

3.1 Research Design

Market research is usually perceived in a business setting when entrepreneurs or companies require data about customers' needs and buying habits. (Hague et al., 2004) However, in this study, the term market research may be defined as the tool or process to gain a better understanding of the condition of the market of interest. (Miller, 2021) In this case, the primary focus would be on the present state of the textile recycling sector and the viable technologies suitable for the Nordic market.

This market research will utilize two sets of data: secondary and primary data. Secondary data comprises of the current state review of the textile recycling industry within the public sector of Northern Finland, Norway, and Sweden, and the conceptual framework which presented the BAT and TRL. Primary data collection via a qualitative method was then utilized to seek information that could answer the second research question and meet the second research objective.

Qualitative method of data collection refers to the gathering of non-numerical data which could be words or text, audio, or even images. This method is usually used to gain insights on a specific context. (Elo & Kyngäs, 2008) In a study exploring the transition of linear to circular textiles, the researcher utilized a qualitative method by conducting interviews with industry experts to learn their viewpoints on the topic. (Laukkanen, 2022) In a similar way, this market research conducted interviews to learn the target industry experts' outlook on the current and potential landscape of the industry in the areas of interest.

3.1.1 Secondary Data

Secondary data refers to data easily accessible from different sources such as books, libraries, and online sources. (Adams et al., 2007) Ideally, based on the information hierarchy, academic articles in peer-reviewed journals are considered the gold standard when conducting research. (*Research 101: Hierarchy of Sources*, 2023) Other reputable sources are books by experts as well as government publications. Information and updates from mainstream news outlets are also considered credible and valuable. On the other hand, magazines and organizational websites offer insights with varying reliability, thus should be approached with caution. At the bottom of the pyramid are blogs and social media.

The researcher utilized mostly materials available online or digitally. Educational databases such as Theseus and Finna were used to find similar research papers to provide a basis for the layout and flow of the thesis. For more technical information needed, the researcher used Google Scholar and ScienceDirect to find peer-reviewed articles specifically about available recycling technologies and their application. Terminologies presented in these articles, as well as from e-books and online dictionaries, are also used to provide definitions for unfamiliar concepts in this study.

As university-level research, it is imperative that peer-reviewed articles are used as secondary sources. Peer review involves dedicated researchers taking the time to assess submitted papers, not only to validate the work but also to contribute constructive feedback for improvement. This process ensures that published research meets high standards of truthfulness and accuracy. Through this practice and system, the overall reliability and credibility of the information included in research papers are enhanced. (Steer & Ernst, 2021) Consequently, gathering data directly from sources such as blogs and Wikipedia should be avoided as it is more difficult to check their validity especially if their references are not readily available.

In addition, use of appropriate webpages as sources is maximized as the research requires up-to-date information regarding the textile waste recycling industry. Hence, webpages which contain updates from the EU such as the European Innovation Council and SMEs Executive Agency (EISMEA), the European Commission (EC), the European Parliament, and other news websites are continuously checked and used as basis for situation developments on the industry.

Official websites are also used as sources as the research often requires information about certain companies. In addition, organizations usually have webpages that provide detailed information about their own research and study on the industry or technologies they utilize, which are helpful foundations for the thesis. Lastly, the thesis commissioner also continuously provides the researcher with materials that may help with the thesis writing. These materials range from journal articles, reports, and summaries of studies or data gathered for the ongoing THREAD project.

Contrary to the common practice of utilizing secondary data to validate the primary data, this research used the secondary data presented as basis for constructing questions that lead to the primary data collection.

3.1.2 Primary Data

As a bachelor's degree-level thesis, collection of primary data is mandatory in the researcher's university. Simply, primary data is one's original gathered data via appropriate method/s. (Adams et al., 2007) Aside from this being a requirement, the researcher deem primary data collection essential as these could provide more in-depth information to answer the research questions.

Primary data collection is usually categorized between quantitative and qualitative. Quantitative data collection requires large data sets and uses statistical methods to analyze collected data. On the other hand, qualitative data collection, which will be used to gather primary data on this research, does not rely on numbers. Its aim is to gain an in-depth understanding of topics of interest. (Kortelainen, 2023, slides 4-5)

In this research, in-depth expert interviews were conducted to obtain primary data. Qualitative data collection usually relies on a few in-depth cases to study. For this research, 4 industry experts agreed to take part in the interviews.

In the results section, content analysis was conducted to assess and present the gathered data. Content analysis is a research method that may be used for either quantitative or qualitative data. Its goal is to analyze the provided data and be able to process and group these into more content-related or more understandable categories. (Elo & Kyngäs, 2008) In this case, collected primary data from interviewees were categorized based on the themes that arose from their responses.

Participants

A purposive or deliberate method of sampling was used for this research. This meant that the researcher selected a sample based on the knowledge about the population as well as for the purpose of the study. (Glen, n.d.) This method was employed as it allowed the researcher to focus on individuals who possess the desired expertise and experiences necessary to answer the interview questions. Purposive sampling is chosen when researchers seek to maximize the relevance and richness of the data by intentionally selecting participants who can provide valuable perspectives or information related to the study's purpose.

The researcher aimed to interview at least 3 industry experts for this study; one from each area of interest. In this research, industry experts refer to professionals with specialized knowledge, experience, and expertise in the management and handling of textile waste within the industry. This may include waste management officers, professors, researchers, and other professionals who possess comprehensive understanding and insights into the processes, challenges, and innovations related to textile waste management. Along with the assistance of the commissioner, the researcher was able to gather data from 4 interviewees, 2 of which comes from Finland. Table 4 introduces the interviewees.

Identifier	**Location**	**Name**	**Role & Affiliation**
Interviewee A	Finland	Ms. Henna Knuutila	Senior Lecturer, Turku University of Applied Sciences
Interviewee B	Finland	Ms. Mirva Lindström	Work Trainer, Kittilä Recycling Center
Interviewee C	Norway	Mr. Petter Hofstad Strand	Project Manager, Remiks Oy
Interviewee D	Sweden	Ms. Jamilla Nilsson	Project Manager, RISE Research Institutes of Sweden

Table 4. Research Interviewees

3.2 Research Procedure

This section presents the systematic procedure employed in this study, encompassing the data collection methods, analysis technique, and interpretation.

3.2.1 Data Collection

The collection of primary qualitative data was conducted in October 2023. Providing this data allows the readers to understand the contextual background of the interviewees' answers. Various industry experts were approached with the goal of finding representatives of the textile waste management industry for the three countries. Expectedly, not all target interviewees responded to the invitations, hence, the representativeness of the sample remains limited.

The researcher has formulated 10 interview questions that aim to provide information for the second research question. To reiterate, the second research question is aligned with the objective of exploring the current situation of textile waste recycling in the Northern regions of Finland, Norway, and Sweden by asking about matters such as current practices, challenges, and the potentials of the industry. Further, with a goal of identifying the necessity and if applicable, the type of textile waste recycling technology for the areas, questions regarding this are included.

The interview questions have also been formulated based on information presented in chapter 2. Specifically, regarding the current textile waste collection practices and information about the adaptation of the EPR for textiles. Due to the differences in each country's situation and practices, the list of questions for each country varies slightly.

A semi-structured interview was followed. This means that the researcher, as mentioned, has a prepared list of questions, but their order, as well as the possibility of adding or omitting necessary ones may be expected. (George, 2023) This is because the interviewees' affiliations, positions, and scope differ, hence, adapting the interview accordingly was found essential.

Prior to the interviews, either or both the thesis commissioner or the researcher reached out to the potential interviewees to ask for the possibility of an interview. Once they have confirmed their interest, the researcher sent the informed consent form and the interview questions. The form and the questions are found in Appendices 2 and 3, respectively. From the researcher's perspective, this allowed the participants to make a more informed decision before fully agreeing to partake in the interview. Also, the interview was conducted in English, the language at which the thesis is required to be. Therefore, this practice allowed the interviewees, whose first language may not be English, to prepare their answers.

The interviews were conducted online via Teams and lasted between 30 minutes to an hour as planned. During the interview, permission to record the conversation was asked at the start and acted upon accordingly. The interviews were then transcribed automatically via the Teams application.

3.2.2 Data Analysis

The researcher then conducted a qualitative content analysis based on the transcription to summarize and analyze the data according to the research questions. Qualitative content analysis is one research method that allows the systematic examination of textual or visual data to discern patterns, themes, and meanings. It aims to provide a comprehensive understanding of the content under investigation by examining the context, structure, and content of the collected data. Unlike quantitative content analysis, which focuses on counting and categorizing data, qualitative content analysis emphasizes the interpretation and contextualization of the data. Simply, this method would allow the researcher to look for similarities and differences among the collected responses. (Glen, n.d.)

Once the interviews have been transcribed, the researcher established a coding scheme to structurally organize the data. A coding scheme is a set of categories or labels that researchers assign to different segments of the data based on their content or meaning. Utilizing this facilitated in breaking down the information into manageable units, thereby simplifying the identification of patterns, themes, and relationships during the analysis phase.

Subsequently, the researcher organized the data based on the codes by manually highlighting and/or setting a different font color to the text to create a visual representation of the segments. Once the data has been grouped per color, the researcher identified patterns within the coded segments. This involved looking for connections, relationships, and recurring patterns that provide insights into the research question or topic of interest.

3.2.3 Data Interpretation

The final step was interpreting the data by drawing the key findings based on the identified themes and patterns. This encompassed synthesizing the discoveries, establishing connections to existing literature or theories, and providing explanations or insights into the research question or topic.

Finally, in the conclusion, the researcher summarized the key points of the study, provided further insights to the key findings, and assessed if the study achieved its objectives. Evaluating research may be based on qualitative measures such as peer reviews and quantitative measures by using mathematical methods in evaluating the impact of the publication. (*Research Evaluation*, n.d.) In this case, the completion of the study would be one indicator of success. Nevertheless, the overall aim is to contribute to the THREAD project's research and development by potentially identifying a commercially suitable recycling technology for the northern regions included.

Figure 2 presents the main activities included in the research procedure while Appendix 2 provides the planned work schedule to carry out said procedure.

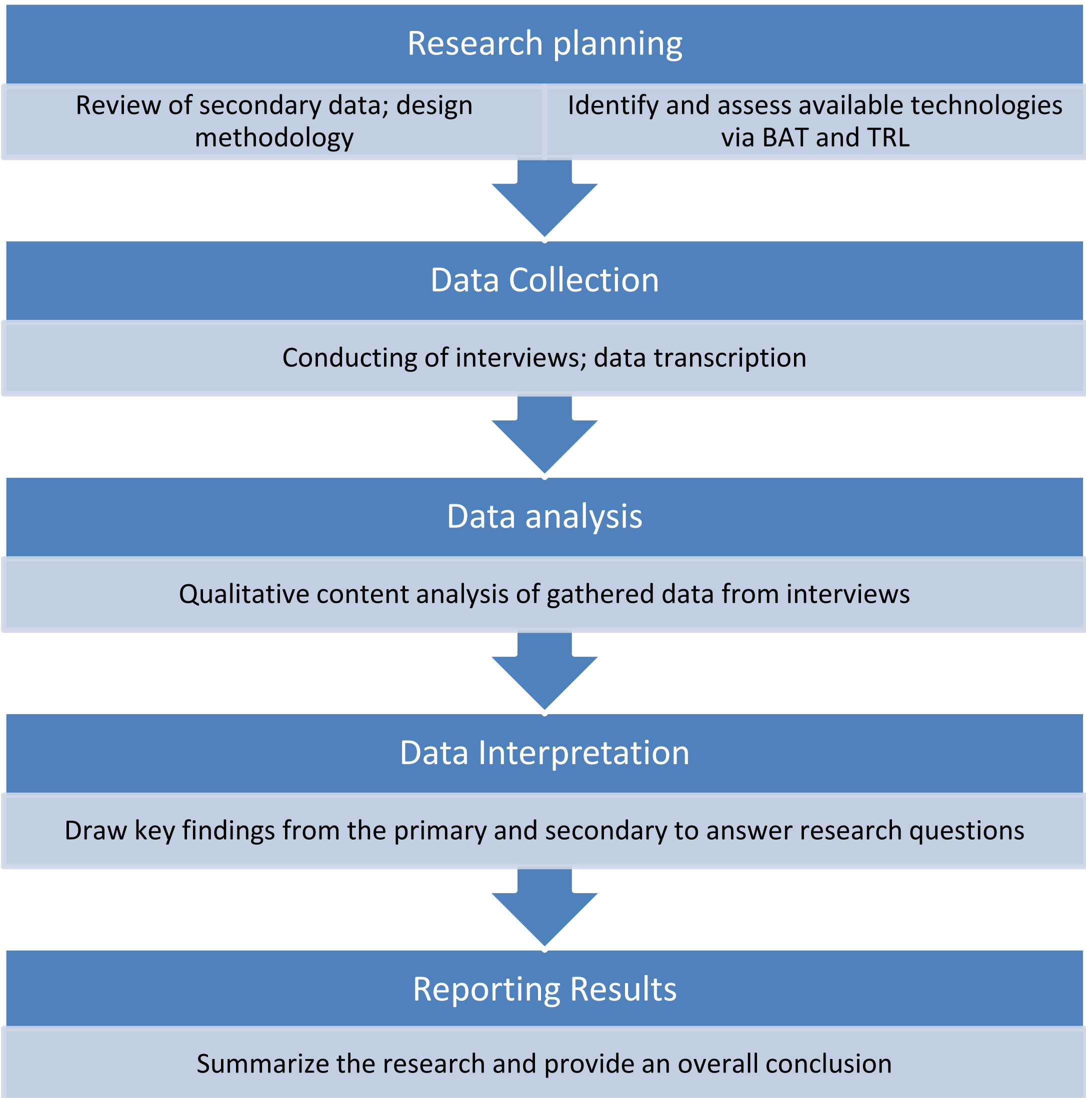

Figure 2. Research Procedure Flow

3.3 Reliability, Validity, & Ethical Considerations

This section comprehensively outlines several critical aspects that must be considered in the research process, namely reliability, validity, and ethical considerations.

3.3.1 Reliability

Reliability often refers to the "consistency" of a measurement. (Kelley, 1999) It may also be understood as the extent to which the research, its methodology, and findings can be replicated. (Kopala & Suzuki, 1999)

In this research, primary data is gathered through qualitative methods, specifically interviews. The reliability and validity of qualitative data have been subjects of ongoing debate (Kopala & Suzuki, 1999). Despite these debates, this research is meticulously documented and structured to enhance replicability by other researchers. Detailed research procedures and tool overviews are provided to ensure transparency and facilitate reproducibility. However, it is essential to acknowledge the potential limitations in the reliability of this thesis, primarily attributable to the use of purposive sampling.

Adopting this sampling method raises potential implications for the reliability of the process. This could eventually contribute to researcher bias which is the possibility of influencing the research findings to suit or match the researcher's own beliefs. (Ingram, 2023) While there may be indications of selection bias, it is crucial to clarify that the choice of interviewees is rooted in their specific affiliations and expertise, not with the intention of seeking validation for any presented theory. Importantly, the researcher maintains objectivity by lacking any affiliations with the target interviewees. Recognizing the inherent potential for bias, the researcher remains consciously aware and committed to upholding objectivity when engaging with respondents throughout the research process.

The primary and secondary data showcased in this research may exhibit variations from other existing sources, which emphasizes the contextual and case-specific nature of the study. Consequently, other researchers exploring the same study might opt for alternative tools or methodologies to replicate or extend this research. The uniqueness of each case underscores the importance of considering diverse sources and methods in the pursuit of a comprehensive understanding within the broader research landscape. Still, as explained in section 3.1.1, the researcher understands the hierarchy of secondary sources and has diligently utilized reputable sources in the pursuit of providing reliable data.

3.3.2 Validity

Validity is defined as the extent to which research results are true or accurate. (Kopala & Suzuki, 1999) The researcher acknowledges the validity constraints inherent in the thesis, attributable to the restricted timeframe of the research and the limited number of participants available for interviews.

Due to the qualitative method of primary data collection, it is important to that the interviewees' views may differ from other experts in the field. Nonetheless, the researcher will report the interviewees' expert opinions objectively. As previously noted, the researcher intentionally provided the interview questions to participants in advance, to enable a more informed decision and preparedness for interviews conducted in English. Nonetheless, the researcher understands that this practice introduces the possibility of response bias, possibly impacting the overall validity of the study. Response bias is a general term used when a respondent such as an interviewee provides answers that may not be their own, genuine opinions. (Ingram, 2023) In this case, knowing the questions before the interview exposes the risk of rehearsing specific answers and minimizes the spontaneity of the interview.

To at least minimize the negative impacts of sending the questions before the interview, the researcher will reiterate the importance of genuine responses based on the experts' own knowledge and experiences. Follow-up questions would also be asked to probe deeper into the respondents' answers or explore necessary, unexpected topics.

In addition, the possibility of research bias may also impact the validity of the results. As explained in the earlier chapters, specific variables studied in this research were predetermined and provided by the commissioners. Thus, these factors would also be explored during the interviews. Nonetheless, the researcher does not aim to validate the appropriateness of these factors, rather, gain a wider perspective of the textile waste recycling industry via the interviews.

The generalizability of the research is also limited due to the focus on the three specific countries and regions within the Nordic. This would mean that findings that may be applicable to the areas of interest may not be applicable to other areas. (Glen, n.d.) Furthermore, the representativeness of the industry experts to be interviewed, which refers to the ability of a sample to reflect a larger group (Insight Assessment, 2023), may be low as purposive sampling has been utilized to choose the interviewees. However, other interested researchers, organizations, or companies may still benefit from this research should they require data on available textile waste recycling technologies.

3.3.3 Ethical Considerations

The researcher is also aware of the ethical considerations when conducting research. This refers to the principles or guidelines one should consider to ensure the research is conducted in an ethical manner. These would include matters such as interviewees' rights and well-being, as well as the integrity and credibility of the research. (Hassan, 2023)

As the expert opinions of the interviewees were pertinent to the study, their professional affiliations and identities were deemed relevant. Consequently, rather than prioritizing the anonymity of the interviewees, the researcher sought the informed consent of the participants. Consent forms were distributed, consisting of the research's goals and purpose, along with an explanation of the interviewees' rights. Permission to include their names on the research was obtained, provided that the researcher will share the final version of the thesis to the interviewees prior its publication affording them an opportunity to review for any potential misinterpretations, misunderstandings, or misrepresentations.

As for the research itself, the commissioner has not stated any restrictions on the publication of the results nor the thesis itself. Conversely, data transparency is encouraged to enable replication or furthering of the research. Through this, the validity of the study may increase or could generally contribute further to the research and development of the industry. (Hassan, 2023)

4 Data and Results

In this section, the analyzed data from the interviews will be presented. There will be 3 main parts: 4.1 presents an overview of the textile waste recycling landscape for the three countries/areas; 4.2 explores interviewees' expert opinions regarding the possibility of investing on recycling technologies; and lastly, 4.3 provides a discussion about the Extended Producer's Responsibility on textiles.

4.1 Overview of the Recycling Landscape

In section 2.1, a current state review of each area was presented using only secondary sources. For the first interview questions, a brief overview, developments, and challenges in the textile waste recycling landscape for each area were asked to the interviewees to enable comparison or validation between secondary and primary data sources, as well as to supplement the information further.

For Finland, both interviewees explained that the collection of textile waste was initiated at the start of 2023. Interviewee A confirms the pioneering companies for this practice which are LSJH and Rester Oy along with the efforts of Telaketju, and that the practices extend to the Northern parts of Finland, facilitated by the proactive involvement and support of municipalities and regional waste management companies.

On the other hand, Interviewee B explained that for Lapland, specifically, which is the largest and northernmost region in the country, a company called Lapeco has been collecting textile waste from 9 joint municipal authorities. These collected textiles then undergoes pre-sorting and further sorting in several locations such as an experimental pre-sorting facility in Kittilä and Oulu's sorting center. Then, materials suitable for cellulose recycling will be sent to Paimio wherein LSJH and/or Rester Oy are located.

Regarding collaborative efforts, Interviewee B mentioned that there are no official cooperative agreements between municipalities and Helsinki's metropolitan area. However, she explained that as waste management companies are owned by municipalities, these companies collaborate with one another as well as with other organizations not only to identify suitable destinations for the collected materials, but also practice information-sharing.

As for Northern Norway, Interviewee C confirmed that there is no material recycling as there is currently no infrastructure that exists in the area for this. Further, he shared that there are no official waste collection systems in place yet, but there are organizations and/or companies that collect and resell end-of-life textiles on a voluntary basis – which confirms the data in 2.1.4. By the end of 2023, there should be a general recommendation whether a pick-up or drop-off system will be utilized by municipalities, but waste companies are leaning toward drop-off systems as this would be a cheaper option rather than collecting waste separately.

In Northern Sweden, Interviewee D explained that there is not a big difference between the textile collection practices for the Northern and Southern parts of the country. The NGOs gather all textiles from their own shops, Recycling Stations (previously managed by producer organizations for packaging, but from January 1, 2024, overseen by municipalities), and some Recycling Centers (operated by municipalities). They then categorize items suitable for resale as second-hand in Sweden and segregate textile waste. The remainder is shipped to European countries for sorting for potential second-hand use there. By 2025, municipalities will be obligated, as per the waste framework directive (WFD), to separately collect textiles - which is also in line with the secondary data gathered in 2.1.5. However, the sorting of textiles may not necessarily be conducted by municipalities; it could be managed by another organization. Further, textile wastes may already be brought to municipalities' drop-off stations and secondhand shops. Meanwhile, in Gothenburg, Sweden's second largest city and home to fashion companies such as Lindex, KappAhl, and Nudie (TEXTILES AND FASHION, n.d.), owners of apartment buildings can order textile waste collection services, the waste will be collected according to a specified schedule.

Regarding collaborations, Interviewee D shares that the municipalities are highly autonomous, but information-sharing is also practiced as it is not uncommon for several municipalities to own a waste management company together. As an example, in the Gothenburg region, there is a waste company management called Renova which is reported to be owned by 10 municipalities.

Table 5 summarizes these data.

	Collection of Textile Waste	**Collaborations among Municipalities**
Finland	Started in 2023 LSJH and Telaketju are pioneers in collecting household textile waste; municipalities follow	Multiple municipalities own waste management companies and work together to determine the optimal destination

	Rester Oy from other waste streams	for textile waste; no official collaboration with the capital area, Helsinki
Norway	To follow directive by 2025 No official waste collection system yet; certain organizations and/or companies voluntarily collect and resell end-of-life textiles	Bigger cities can operate independently whereas smaller cities in similar situations collaborate and share resources
Sweden	To follow directive by 2025 NGOs actively involved in collecting reusable textile waste for resale, with textile waste being deposited at municipal drop-off stations and secondhand shops	Considerable autonomy of municipalities Emphasis on information-sharing, with instances where multiple municipalities jointly own waste management companies

Table 5. Collection of Textile Waste & Collaborations

Challenges and obstacles in the landscape

In the literature review, it was established that these northern areas of each country share similarities specifically in their geographical conditions and populations. When asked about the challenges and/or obstacles faced in the textile waste recycling industry, there were also common responses among the interviewees.

First, the sparse population in these areas poses several challenges. Because of the substantial distances among municipalities which create obstacles in efficiently gathering all the waste and leads to significant difficulties in waste collection logistics. The vast expanses result in high transportation and shipping costs, given the described comparatively low volume of waste generated in these areas.

Another challenge is the general lack of infrastructure within the areas. This extends to the absence of recycling facilities, with only sorting facilities available. Existing recycling sorting facilities have limited capacity, and these are also situated in locations which necessitate careful transportation of textile waste from the northern regions to prevent spoilage due to extreme weather conditions. This logistical consideration not only incurs further costs, but also adds a layer of complexity to the textile waste management process.

In addition, the interviewees report that the low volume of collected waste poses a challenge to investing infrastructures in these areas. Given the relatively small quantities of waste generated, establishing, and maintaining recycling and sorting facilities may not be deemed commercially viable.

A third challenge would be regarding the mix of textile materials collected. This challenge pertains to the types of waste collected such as reusable textile, actual textile waste, and even shoes and toys. Complicating this challenge further is the mixture or blend of various materials on the textiles. Both these aspects require sorting – manual sorting of the various waste and the processing of textile waste to separate blended or interwoven fibers.

Beyond the primary challenges discussed earlier, Interviewee A emphasized an additional obstacle: not all collected textile waste comes with information about their material composition. This poses an additional barrier, considering that such information is vital for specific recycling processes to take place effectively.

Table 6 summarizes these challenges.

Challenges	Implications
Sparse population	Difficulty collecting waste; low volume
Lack of infrastructure	Needs to be transported to farther facilities; entails cost
Mixture and blend of materials	Difficulty sorting; difficulty recycling
Other: Lack of information with material composition of textiles	

Table 6. Textile Recycling Landscape Challenges Summary

4.2 Textile Waste Recycling Technology Investment

After establishing an overview of the recycling landscape in the three areas, the interviewees were asked about their opinion regarding the possibility and the necessity of investing in recycling technology or a facility within these northern areas.

Both interviewees from Finland mentioned Infinited Fiber which is set to start its operation by 2025. However, it should be noted that Infinited Fiber exclusively focuses on recycling cellulosic fibers such as cotton, viscose, and lyocell and does not handle synthetic fibers or wool. Interviewee A also shared that it may be unnecessary or redundant to have identical technologies in several areas in Finland, hence, this underscores the opportunity to explore alternative recycling technologies, especially for other textile materials not covered by current or upcoming facilities.

As per the insights provided by the interviewees from Norway and Sweden, the practicality of investing in a textile recycling facility or technology in their northern regions remains uncertain due to the relatively low tonnage or volume of collected textile waste. However, Interviewee C points out that if a facility is established in the northern regions of Finland, Norway, or Sweden, it could conceivably serve as a centralized location where textile waste from these areas can be directed.

Inquiries about what other factors should be considered for the possibility of investing in a facility. Undoubtedly, the volume of collected waste stands out as one of the most important factors. Other factors or considerations would be the location of the facility as proper transportation is known to be costly; the mixture and quality of textile waste such as what types of textiles are there and their fiber composition; what recycled products are in demand or are needed by different companies, industries, and consumers; environmental permissions; and lastly, it should also be considered whether local municipalities are able to pre-sort the textile waste before sending them to the recycling facility.

Finally, interviewees were also asked if they had specific recycling technologies in mind that may be feasible for the northern areas. The common response is that they cannot recommend a specific technology due to numerous factors to consider. However, Interviewee C mentioned several technologies or methods that may be explored which are the BAT identified in section 2.2.1; Interviewee B also mentioned the possibility of exploring utilization of waste in construction, insulation, and using the products extracted from waste for building materials that could potentially replace new plastic materials – such as what the French FaBrick already does.

Table 7 summarizes the aforementioned factors.

Factors to consider when identifying feasible textile recycling technologies		
Volume of textile waste	Variety, quality, and material composition of collected textile wastes	Compliance with environmental regulations
Locations of the recycling facilities	Demand for recycled products	Capacity of local municipalities to pre-sort the waste

Table 7. Factors to consider when identifying feasible textile recycling technologies

4.3 Extended Producer's Responsibility

At the latter part of the interviews, the topic of the Extended Producer's Responsibility was also discussed.

The prevalent theme among the interviewees' responses is that the EPR is a promising policy in theory, but the specifics should still be clarified to ensure its effective implementation. Their common concern is how producers will manage their textile waste and that the EPR should include restrictions on exporting waste to other countries and instead identify and utilize profitable local recycling methods in a sustainable manner.

Another recurring theme from the responses revolves around the fact that 80% of the environmental impact of the textile industry comes from the production phase. This strengthens the need for producers to not only be responsible for their textile waste, but also to the conscientious design of their textile products. This entails considerations like restricting the use of mixed fibers to enable easier sorting and recycling, and the use of high-quality materials that ensures durability and imminently reduces consumption. Producers should also consider the serviceability of their products, which would allow repairs or alterations. In addition, producers should help in overall promotion of sustainability such as sharing care instructions on the products and advocating against fast fashion.

All interviewees confirmed that the EPR is not yet implemented in these 3 countries and that further discussions and decision-making are still ongoing on the EU level.

5 Discussion of Key Findings

In this section, the key findings will be discussed. This includes interpreting and explaining the results and connecting them with existing knowledge or literature. Below, the three research questions will be presented to organize the synthesized key findings from secondary and primary data.

5.1 What technologies are currently available for textile waste recycling?

Various innovative recycling technologies have been developed to address the issue of textile waste directly, providing a variety of solutions to convert textile waste into valuable resources. Textile waste offers vast potential and may be used as insulation materials, acoustic panels, geotextiles, bricks, and concrete reinforcement, and generally be utilized for green building materials.

There are other research studies which focus on textile waste being used for these purposes, but in this research, the focus was on fiber-to-fiber technologies as it is reported that this method is the most sustainable for being low cost and energy-efficient compared to other recycling technologies. (McKinsey & Company, 2022)

Five textile recycling technologies' categories were identified in this research: mechanical, thermal, thermo-mechanical, chemical method which includes pulping, solvent-based, and depolymerization processes such as glycolysis, methanolysis, and hydrolysis, and thermo-chemical such as pyrolysis and hydrothermal liquefaction.

Based on secondary sources, it is found that some companies have started utilizing mechanical, thermo-mechanical, pulping, depolymerization, and methanolysis technologies commercially. Other technologies may be used in a pilot-scale setting or are tested and developed in laboratories. While the textile waste recycling industry is still considered to be in its early stages, significant advancements like these indicate a promising rate of progress within the field.

5.2 What is the present state of textile waste recycling within the public sectors of Northern Finland, Norway, and Sweden?

5.2.1 Northern Finland

Textile waste collection started in Finland in 2023, led by LSJH and Rester Oy. The practice extends to Northern Finland with support from municipalities and waste management companies. For example, in Lapland, Lapeco collects textile waste from 9 municipal authorities, and the Kainuu region has Entrinki. Pre-sorting and sorting occur in various locations, with suitable materials sent to Paimio. While there are no official cooperative agreements, waste management companies collaborate and share information to determine material destinations.

Based on both secondary and primary sources, it is reported that Infinited Fiber, a circular fashion and textile technology group, is building a fiber recycling facility in Kemi. The flagship plant, with an estimated investment of 220 million EUR, will be operational by 2025. Hence, it was suggested that if other textile recycling technologies or facilities would be invested in, other recycling technologies may also be considered to expand the range of textile waste to be processed.

5.2.2 Northern Norway

In Northern Norway, there is currently no material recycling due to a lack of infrastructure. Official waste collection systems are not yet in place, but some organizations and companies voluntarily collect and resell end-of-life textiles. By the end of 2023, a recommendation should have been made on whether to use a pick-up or drop-off system. Waste companies prefer drop-off systems as they are cheaper. The viability of investing in textile recycling facilities in northern areas is uncertain due to the low volume of collected waste. However, during the interview, it is mentioned that if a facility is established in Finland, Norway, or Sweden, textile waste from the northern regions could be collectively sent there.

5.2.3 Northern Sweden

In Sweden, textile collection practices are similar in the northern and southern parts of the country. Currently, within municipalities, there are collection systems for textiles at Recycling Centers and Recycling Stations, where NGOs gather all textiles and sort them for potential reuse, recycling, and waste disposal. Typically, NGOs separate items for domestic resale and remove the waste fraction, while the remainder is often exported to EU countries for sorting and potential resale or recycling. Starting from January 1, 2025, municipalities will assume responsibility for the separate collection of textile waste, but it is likely that NGOs will continue their practices. Although the waste framework directive promotes the reduction, reuse, and recycling of textiles, there is currently no requirement for sorting or recycling. Furthermore, there are still uncertainties regarding the establishment of the remaining textile handling processes, as the EU has indicated the likelihood of implementing the EPR on textiles in the foreseeable future. Hence, stakeholders are awaiting clarification on the forthcoming requirements.

In general, the three areas share similar challenges in the textile waste recycling landscape. The sparse population in remote areas presents challenges for waste management, with difficulties in collecting waste and high transportation costs. The absence of recycling facilities and the lack of sorting infrastructures further complicates the situation. Additionally, the mix of textile materials and lack of information regarding their composition hinders recycling processes.

Also, the EPR has not been implemented in any of these 3 countries, as discussions are ongoing at the EU level. The interviews reveal that the EPR is a promising policy, but its details need clarification for effective implementation. It is a concern about how producers will manage textile waste and suggest restrictions on exporting waste and promoting local recycling.

It is also highlighted that 80% of the textile industry's environmental impact comes from production, emphasizing the need for responsible waste management and sustainable product design. Producers should prioritize durability, easy sorting and recycling, serviceability, and promoting sustainability. As seen from section 2.1.1, amendments are continuously proposed to improve the key actions and strategies especially towards the improvement and specification of the EPR.

5.3 Among the identified textile recycling technologies, which exhibits the greatest potential to be commercially viable for Northern Finland, Norway, and Sweden?

At this point, the available textile waste recycling technologies have been laid out and their individual strengths and weaknesses have been discussed. Several examples and cases have been included to demonstrate the readiness level of these recycling technologies. In addition, the information and insights gathered from the interviewees provided valuable perspectives into what the industry or the northern areas need.

Notably, at least in the northern part of Finland, there will be a recycling facility by 2025 which will most likely utilize chemical methods such as depolymerization. However, in the northern regions of Norway and Sweden, there are currently no known recycling facilities or plans.

Considering the regions report generating and somehow collecting only a low tonnage of textile waste, it becomes evident that any investment in a textile recycling facility should prioritize minimizing costs. Hence, it is only logical to steer away from intricate technologies like depolymerization methods (glycolysis, methanolysis, and hydrolysis), known for their higher investment requirements. It is also crucial to highlight that while the investment costs mentioned in section 2.2.1 offer valuable insights, they may not directly apply to future investments in the specific areas of focus due to likely variations in size and capacity. Nevertheless, these figures can serve as a useful benchmark for decision-makers in evaluating and planning investments within similar contexts.

Overall, small-scale mechanical methods emerge as suitable solutions for these areas. Recognized for their cost-effectiveness and lower investment demand in comparison to other technologies, these align well with the regions’ challenges. Table 4 also shows that the maturity level of the presented mechanical technologies is approximately at 8-9 as they are utilized commercially. Nonetheless, due to the uncertainty with the implementation of the EPR on textiles for all EU member states, investments in small-scale recycling facilities may not currently be considered.

Furthermore, it should be emphasized that recycling would just be the one of the final solutions for textile waste. Reiterating responsible production and consumption would still be the most crucial factor in reducing the negative impacts of the textile sector.

6 Conclusion

This thesis started with laying out the research background and established that the average European consumer disposes of 12 kilograms of textiles every year. The European Union set out a directive that textiles should be collected separately by 2025; with the urgency stemming from the growing amount of textile waste and ranking fourth in environmental impact in Europe.

Research on the circularity of textiles and the textile waste management industry is still considered to be in its early stages, therefore the study aimed to contribute to the research and development with an objective of potentially identifying a commercially viable textile recycling technology for the northern regions of Finland, Norway, and Sweden, which share similarities to their population and geographical characteristics, and are close in proximity. There were 3 research questions mainly about the available textile recycling technologies and their maturity; the current situation of the textile waste recycling landscape for the 3 areas; and finally, the question of which of the identified technologies would be ideal given the analysis of the areas' landscapes.

The first research question was explored through the conceptual framework of the thesis. The Best Available Techniques method and the Technology Readiness Level index were used to define and assess the textile waste recycling technologies. Secondary data in the literature review and primary data gathered from the interviews were employed to answer the second research question. The collection systems – current practices or plans were discussed, the challenges in the industry were identified, factors to be considered when identifying a suitable recycling technology were presented, and views regarding the EPR were explained.

All the information gathered to answer research questions 1 and 2 were then leveraged to likely provide an answer for the third question. Taking into consideration the challenges and different factors when identifying a feasible textile recycling technology, the choice of employing mechanical methods potentially emerges as a logical approach for addressing textile waste challenges in the designated areas. However, the financial feasibility of such investments is compromised by the scale of waste production, creating a dilemma where the lack of existing infrastructure hampers effective waste management, yet investing in new facilities may not be economically justifiable given the current waste generation rates.

Furthermore, the evolving landscape significantly depends on the specifics of the Extended Producer Responsibility (EPR) on textile and its implementation. The outcome of this policy framework will undoubtedly shape the trajectory of waste management strategies in the coming years. Furthermore, the imminent implementation of the EU waste directive for collecting textile waste next year (2025) introduces a crucial turning point. As the actual volume of textile waste collected for each area will eventually be reported, it will open avenues for further research and a more precise analysis. This forthcoming data will enable a deeper understanding of the local dynamics, facilitating informed decisions, and targeted interventions to optimize waste management practices not just in the northern regions, but for all EU member states.

Lastly, the researcher evaluates the attainment of the thesis objectives. All research questions were addressed thoroughly, leading to comprehensive answers. Notably, the final objective aimed to pinpoint a commercially viable textile waste recycling technology applicable to the three areas of focus. However, amidst the comprehensive analysis, it became apparent that identifying a singular suitable technology presents difficulty at this stage. Nevertheless, this outcome contributes invaluable insights into the prevailing circumstances of the industry, shedding light on its intricate challenges. Moreover, this process serves as a precursor as it presented the prerequisites essential for the eventual identification of a commercially viable recycling technology. Thus, while a definitive technological solution may not have materialized, the pursuit has provided a deeper understanding of the necessities for the development of the textile waste recycling industries within the northern regions of Finland, Sweden, and Norway.

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THREAD Project Summary

KAMK • University of Applied Sciences

Project Summary

- Objective: to explore the feasibility of textile reuse and recycling across the region.
- Interreg Programme Priority - Strengthening the capacity for climate change adaptation, and resource sufficiency in NPA Communities
- Project duration 1.06.2023 – 30.11.2023
- Project partners: Remiks Miljøpark AS, Western Development Commission (Ireland), Kajaani University of Applied Sciences (FI),
- Associate partners: Remode Youth (ReMode)

Interview Informed Consent Form

Informed Consent Form for Interview Participation

(Date Sent)

(Name of Interviewee)

(Company or Affiliation)

Good day, (Interviewee),

My name is Charmaine Medina, a third year Bachelor of Business Administration student from Kajaani University of Applied Sciences (KAMK). For my thesis, I am conducting research about textile recycling in Northern Finland, Norway, and Sweden. This research is commissioned by the THREAD project wherein KAMK is a lead partner, which aims to identify feasible recycling technologies for the areas of interest.

I am reaching out to industry experts such as yourself for the possibility of an interview to gather further information about the situation of the textile waste recycling industry in your area. This information would then be further utilized to hopefully identify suitable technologies for these northern regions.

The interview will be conducted in English and will take place online via Zoom or Microsoft Teams. It will be a semi-structured interview which may last approximately 30 minutes to an hour. The interview questions are provided in advance to provide understanding of the interview topics and ensure a fully informed consent. It should be noted that follow-up questions may be asked to expand or confirm certain responses.

I am hoping that you can share your time and knowledge to aid in my pursuit of information. Nonetheless, your participation in this interview is entirely voluntary, and you have the right to refuse to answer any question or withdraw from the interview at any time without consequences. Further, there are no risks associated with the interview. As for the benefits, your insights will contribute to my research and the field of textile waste recycling. Also, I will be sending you a copy of my final thesis prior its publication on academic archives.

I would also like to emphasize that you may opt to be unnamed in writing, but with your permission, I intend to include at least your professional affiliation and job title, to provide a credible description of the interviewee. In addition, I will be asking for your permission to record the interview to ensure concentration on the duration and avoid overlooking any material brought up in its course.

In line with that, the interview recording will be used solely for transcription and analysis of the content. Access to the recording will be limited to myself and may extend to my thesis commissioner and supervisor, if necessary. An excerpt or summary of the interview will however be used in the thesis and/or presentations. Lastly, the recording will be stored in my thesis cloud drive for at least one year to ensure its availability as reference and verification.

With this, I would like to ask for your participation in an interview for my research. I am hoping to conduct the interview on (Date, Time, & Time zone). Otherwise, please let me know when the best date and time would be for you, so we can schedule accordingly. Should you have any questions or concerns, please feel free to reach out via my email (charmainemedina@kamk.fi).

By signing this, you agree that you have read the contents of this form and voluntarily agree to participate in the interview.

Name, signature, and date signed.

Interview Questions

Interview Questions

Area: Northern Finland

1. Can you provide a brief overview of the current state of textile waste recycling in Northern Finland?
2. What collaborative efforts among municipalities and the capital area engage in to address textile waste? (If any)
3. What challenges and obstacles have you observed exist in the textile waste recycling industry?
4. To your knowledge, are there any operational or planned textile waste recycling facilities in the North of Finland?
5. In your opinion, how necessary would an investment on textile waste recycling technology for Northern Finland be?
6. What are the most notable factors to be considered when identifying suitable textile recycling technology in the area?
7. Are there any innovative technologies or processes that you believe hold great potential for textile waste recycling for the area?
8. In your opinion, what role does the extended producer responsibility (EPR) play in addressing textile waste recycling?
9. What are the implications of the adaptation of the EPR on the development of the textile waste recycling industry?
10. Based on your answers and your expertise, what is your standpoint in implementing the EPR?

Interview Questions

Area: Northern Norway

1. Can you provide an overview of the current state of textile waste recycling in Northern Norway?
2. What are the developments in the industry since the EU directive on sustainable and circular textiles?
3. What are the current/planned collection systems for textile waste in the area?
4. What challenges and obstacles have you observed exist in the textile waste recycling industry?
5. What collaborative efforts among municipalities and the capital area engage in to address textile waste recycling? (If any)
6. In your opinion, how necessary would an investment on textile waste recycling technology for Northern Norway be?
7. What are the most notable factors to be considered when identifying suitable textile recycling technology for the area?
8. Are there any innovative technologies or processes that you believe hold great potential for textile waste recycling in the area?
9. In your opinion, what role does the extended producer responsibility (EPR) play in addressing textile waste recycling?
10. What are the implications of the adaptation of the EPR on the development of the textile waste recycling industry?

Based on your answers and your expertise, what is your standpoint in implementing the EPR?

Interview Questions

Area: Northern Sweden

1. Can you provide a brief overview of the current state of textile waste recycling in the Northern regions of Sweden?
2. What are the developments in the industry since the EU directive on sustainable and circular textiles?
3. What are the existing collection systems in place for textile waste in the area?
4. What are the main challenges and obstacles in the textile recycling industry?
5. What collaborative efforts among municipalities and the capital area engage in to address textile waste recycling? (If any)
6. In your opinion, what role does the extended producer responsibility (EPR) play in addressing textile waste?
7. How effective is the EPR in mandating manufacturers to take responsibility for the entire lifecycle of their products?
8. With the existence of EPR in the country, in your opinion, how necessary would an investment on textile waste recycling technology for Northern Sweden be?
9. What are the most notable factors to be considered when identifying suitable textile recycling technology for the area?
10. Are there any innovative technologies or processes that you believe hold great potential for textile waste recycling in the area?

Qualitative Content Analysis – Codes and Segments

Fi	Collection Schemes & Facilities	Challenges	Collaboration
No	No system in place yet; waste company perspective: drop off is a lot cheaper than collecting waste separately	**Distance; transpo**	**Autonomous**
Se	Discussions on the best ways to collect waste as solution should be implemented by 2025; looking at different ways (bins, deliver to company); recommendation later this year	Vast distance between people and municipalities; sparse population; and spread across a huge area; difficult to collect it bec low volume so	Laws fail to consider smaller and farther cities or municipalities; bigger cities are independent so there is really no collaboration;
	Municipalities; drop off to the stations/centers/ secondhand shops; Gothenburg sign up and a car picks up	Transportation costs are high. Shipping cost is an issue bec it is far and expensive	Lot of autonomy in the municipalities
	North – no infrastructure for F2F sorting and recycling		**Joint ownership**
	NGOs do manual sorting what they can sell, in Eu, then be sorted again what can be sold, material recycling, or just waste	The challenge is the long distances between transports.	not uncommon for few municipalities own waste management company together
	collect textiles from households, started from telaketju; LSJH pioneer; municipalities are responsible of household waste; regional waste management companies – northern parts do the same (collect); Rester other textile waste streams	**Low volume of waste**	Gothenburg region, there is some waste management company called Renova, which is 10 municipalities that is owning it together
		due to low volume, nobody wants to invest in a recycling plant, not commercially viable	Waste management companies are owned by the municipalities
		total amount of textile waste in the region is very low	**Other collaboration**
		however it is not commercially viable due to the low tonnage	share information between or among municipalities
			collaboration with similar cities in the same situation
		Mixture of fibers	
		textiles themselves not so easy to recycle because we have so much mixed fibers	
		textile waste is such a mixture of materials	
		it's so many different materials and textile fibers that they use	
		Qualities and various materials are the big obstacle in recycling to get the better, better quality end product out of that	
		mixed spinning makes it very hard to fiber to fiber recycle them because you have two very different fibers that you need to separate	
		Containers are full of toys, shoes etc.	
		Others (lack of info/ knowledge; geographic condition)	
		don't have exact information about all these materials	
		There is lack of knowledge how to recycle textiles.	
		Rainy summer and autumn create conditions where textiles spoil easily outdoors. Sorting must be done indoors	

Necessity/ Plans	Factors to consider	EPR
"Necessary"	**Distance; transpo**	**Opinions on EPR**
Great if there were an investment either here or N. Fi or N. Se. Collaborate with collected waste and just send it	waste stream has to travel far = high costs in transpo	Good idea on paper; experience with EPR on plastics
development of textile waste recycling is very important development of more extensive recycling of textile waste is very important.	logistics - distance in getting the raw material, where it should be sent after **Technology's cost**	Experience is bad, but EPR idea is a good thing IF implemented correctly and if the true cost is reflected n the EPR This is very important, as the recycling fees for textiles currently come to municipalities
Other options	Tech to be not so expensive because of low tonnage	**Futher clarification**
Not necessary to have many of the same can consider Mech, chem, energy recovery, heard of mixed mech chem, thermochem, chemical	cant be the most high technology and should recycle material and make something valuable out of it if there is a solution like material recycling, smaller scale, cheap to invest	Needs to be clarified a lot, still a big question mark,; more questions than answers at the moment Hasn't started and EPR scheme yet because I think we are currently waiting for what is going to be decided on the EU level
Can consider: Recovery of waste in construction. Insulation, products extracted from waste and building materials could replace new plastic materials	**Other considerations**	Govenment should specify what is allowed to do with the waste, should be some requirements
	Quality inspection, automatic quality check, what is the quality of the product you are producing	**Key concern**
Not for the north; Infinited fiber for chemical fiber recycling in 2 years, Kemi Infinited Fiber company is starting fiber recycling in Kemi	it really depends on the volumes Pre-sorting of textile waste locally in municipalities	Restrictions on the import and sale of disposable clothing should be imposed by means of legislation. Transport of textile waste under producer responsibility, e.g. Asia/Africa should be banned by law. producers start a non-profit company to handle the problem, that usually means exporting the waste somewhere where it's chea you don't want to ship a problem to another country. there are restriction within the EU about exporting waste cannot be avoided when an EPR is implemented
		Local strategies
		Recycling should be done profitably locally in a sustainable way. It's a lot better to handle waste locally if possible The serviceability of products and the recyclability of materials create services and jobs locally
		Others The development of higher quality materials reduces consumption.