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The supply and demand balance of recyclable textiles in the Nordic countries

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A B S T R A C T

The textile industry is on its early steps towards circular economy. Being a highly resource-intensive and waste-generating industry, it is essential to embrace fiber-to-fiber recycling in addressing the increasing textile waste problem. Several innovative initiatives are happening within this area, not least in the Nordic countries, where automated sorting and fiber-to-fiber recycling technologies and capacities are developing. These large investments require economy of scale; however, this is challenged by the fractioned supply due to the specific fiber requirements of the recycling facilities. To ensure economy of scale and support strategic planning, it is important to investigate the balance of the demand of those capacities with the supply of recyclables generated in the region. Local and regional perspectives are needed in order to avoid unnecessary transportation of low value materials. Based on a synthetises of existing textile flow studies and interviews with relevant actors in four Nordic countries, this study investigates the balance between the supply of recyclable textiles and the sorting and recycling capacity. This is accomplished by estimating the volumes of recyclables and their fiber composition (based on developed weighting average method) and comparing these with the current and upcoming capacities in each country and in the Nordics as a whole. The findings indicate that the upcoming automatic sorting and recycling capacity will be sufficient to deal with the total recyclable fraction in the Nordic region, except for some of the synthetic fibers. However, there are imbalances between supply and demand within individual countries, highlighting opportunities for collaboration.

1. Introduction

The textile industry is among the most resource-consuming industries, with a vast environmental impact (Amicarelli and Bux, 2022), making it important to develop circularity for end-of-life (EOL) textiles (McKinsey and Company, 2022). In the EU alone, home textiles, e.g., bed linens and tablecloths, and clothing are the fourth most polluting products when viewed from a life-cycle perspective (Nørup et al., 2018; Amicarelli et al., 2022). Most (64 %) of global textile fiber production is based on petrochemicals (polyester, polyamide, and other synthetics), linked to high carbon dioxide emissions. The second largest fiber, cotton, representing 22 % of global fiber production, exhibits high environmental impact via water depletion and toxic pollution due to the use of pesticides (Sandin et al., 2019; Textile Exchange, 2022). Annual purchase by an average European is 26 kg new textiles (Amicarelli and Bux, 2022), thereby generating 15 kg of EOL textiles (McKinsey and Company, 2022). In addition to households, EOL textiles stem from public and private institutions (e.g., police, laundries, hospitals, hotels, and restaurants) (Watson et al., 2020a). On average, 37 % of EOL textiles are collected separately in the EU (Amicarelli et al., 2022), whereas the majority are destined to residual waste for incineration or landfill (Koszewska, 2018; Manshoven et al., 2019). Most of these textiles could have been reused or recycled, decreasing the need for virgin material production (McKinsey and Company, 2022).

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The Nordic countries represent one of the leading regions transforming this industry toward circular economy (e.g., Jia et al., 2020) and have a long tradition of collaborating to develop and design solutions for the benefit of the environment and business. Stimulated by a European Parliament directive obliging member states to set up separate collection of textiles by 2025, municipal actors, non-governmental organisations (NGOs) and commercial actors are actively testing and implementing separate collection solutions, and thus, the collected EOL textile volumes are expected to grow remarkably (e.g., Dahlbo et al., 2017). In particular, the EOL textile fraction that is not suitable for reuse but can be recycled, referred to as recyclables, will grow. In addition, many countries have restricted the import of EOL textiles, foremost, to protect domestic textile industries from competition (IVA, 2020), thus the export of low quality EOL textiles will no longer be possible. This challenges the current practice where most of the collected EOL textile in the Nordic region is exported to the Baltic countries and Central Europe for sorting at large-scale plants (Watson et al., 2020a).

Today, the most established way to recycle textiles is through mechanical recycling and downcycling, in which textiles are shredded and used in rags, isolation panels, or mats (Palm et al., 2015; Lexén et al., 2016; Schmidt et al., 2016). Still, the market for downcycled textiles is close to saturation (Dubois et al., 2020), creating a need for large-scale fibre-to-fibre (F-to-F) recycling turning textile waste into new fibers for producing textile products (Schmidt et al., 2016; Koszewska, 2018; Dubois et al., 2020). The share of recycled fibers slightly increased from 8.4 % in 2020 to 8.9 % in 2021, mainly due to an increase in bottle-based polyester fiber (Textile Exchange, 2022). Still, <1 % of the global fiber market is derived from pre- and post-consumer recycled textiles in 2021.

Several innovative initiatives are generated within EOL textiles, not least in the Nordic countries, where many automated sorting and fiber-to-fiber recycling facilities are emerging. F-to-F recycling technologies require specified fabric and fiber types (e.g., pure cotton, polyester, or wool) or have other specifications, such as color. This indicates that the total supply of recyclables, consisting of a variable group of materials in terms of volumes, quality, and content, must be divided into such fractions that can supply a specific recycling process, hence complicating the economy of scale at the new sorting and recycling facilities. Because F-to-F recycling facilities and EOL textile supply chains are still emerging, it is crucial to know the potential supply volumes in the Nordic region for appropriate strategic planning of sorting and recycling capacities and ensure their sustainability (Baxter et al., 2018) and economy of scale (Fleischmann et al., 2000). Local and regional perspectives are needed in order to avoid unnecessary transportation and stocking of low value materials and to treat them in close proximity to where they emerge (Zhuravleva and Aminoff, 2021).

Recent research in the Nordics has provided valuable results in the context of EOL textiles. For example, an interview-based study by Ljungkvist et al. (2018) concluded that F-to-F recycling should be favored instead of the currently predominating downcycling practices. Further, research has revealed the potential environmental benefits of recycling systems (Zamani et al., 2015; Sandin and Peters, 2018), models of circular business ecosystems (Fontell and Heikkilä, 2017; Salmi and Kaipia, 2022), and the inhibitors of F-to-F recycling systems in the Scandinavian fashion industry (Sandvik and Stubbs, 2019). To strengthen the viability of the emerging sorting and recycling capacity and thus increase the recycling rate for EOL textiles, there is a need to understand the supply and demand balance of these textiles (Zhuravleva and Aminoff, 2021). Thus, the purpose of this study is to explore the *supply* of recyclable textile volumes and the *demand*, studied in terms of the local capacity for dealing with the expected volumes, i.e. existing and upcoming capacity for automated sorting and recycling in four Nordic countries: Finland, Norway, Denmark, and Sweden. Two research questions are formulated to achieve this goal:

What are the expected supply volumes of recyclable textiles in the Nordic countries and their fiber compositions?
How can the current and upcoming sorting and recycling capacity (demand) in the Nordic region deal with the estimated volumes of recyclable textiles?

To guide government actions and increase knowledge on circularity possibilities, this study focuses on the supply–demand balance for EOL textiles in the Nordic countries and points out collaboration possibilities in this region, thereby complementing existing studies (e.g., Tojo et al., 2012; SMED, 2018; Watson et al., 2018; Thorin and Johannessen, 2020; Dahlbo et al., 2021).

2. Materials and methods

To answer the first research question, a secondary data analysis method was used (Johnston, 2014). Several valuable Nordic studies were identified, which focus on country-level textile flows, including EOL textiles. Section 2.1 presents the data sources and analysis approach used to estimate the supply of recyclable textiles within the Nordics, while Section 2.2 elaborates on the data sources and analysis approach used to estimate the volumes of various fiber compositions. To answer the second research question, interviews were conducted, as presented in Section 2.3. Section 2.4 discusses the research quality of this study.

2.1. Estimating supply volumes of recyclable textiles in the Nordics

2.1.1. Data basis for analysis

Previous studies of EOL textile flows (e.g., Watson et al., 2020a; Dahlbo et al., 2021) have identified fractions that are potential constituents of the volumes of recyclable textiles within each country. These fractions are elaborated on further, and their values in each country are presented in Table 1. *Textiles recycled in the country* and *Textiles recycled abroad* refer to home textiles and clothing from households, as well as from public and private institutions, that have been sorted and recycled in the country of collection or exported and recycled abroad, respectively. *Textiles from households, incinerated* refers to the fraction in the residual waste or at recycling centers that is energy recovered. Lastly, *Textiles from public and private institutions, incinerated* refers to the energy recovery fraction from public and private institutions.

Table 1 shows that the two parameters about incinerated fractions represent quite large volumes, and it is important to further understand how much of those volumes could be recycled. Two studies (Table 2) have investigated the share of textile waste generated from households that could have been reused or recycled if separately collected. A Danish national study (Watson et al., 2018) investigates the quality of textiles in

Table 1
EOL textile volumes in four Nordic countries (ton/year), with potential impact on the volumes of recyclables.

Potential sources of recyclables	Denmark (Watson et al., 2018)	Finland (Dahlbo et al., 2021)	Norway (Watson et al., 2020b)	Sweden (SMED, 2018; SOU, 2020)	Total volumes in the Nordics
Textiles recycled in the country	420 tons	624 tons	95 tons	653 tons	1,792 tons
Textiles recycled abroad	5,150 tons	275 tons	6,590 tons	4,605 tons	16,620 tons
Textiles from households, incinerated	39,900 tons	40,376 tons	31,550 tons	72,000 tons	183,826 tons
Textiles from public/private institutions, incinerated	9,020 tons	1,132 tons	9,600 tons	87 tons	19,839 tons

Table 2
Overview of reviewed articles and findings on EOL textile recyclable fraction (AW – apartment waste; HW – house waste; RW – residual waste; SC – small combustible; C – clothing, HT – home textile).

Reference	Source of textile waste	Sample size of clothing and home textile	Recyclable fraction in a particular category	
Watson et al. (2018)	RW (from seven municipalities)	84 kg (AW)	20.7 % (AW)	32.4 % (AW)
		84 kg (HW)	28 % (HW) (existing recycling markets)	41 % (HW) (future recycling markets)
Nørup et al. (2018)	RW and SC (each coming from one municipality)	32.8 kg (RW) 276.6 kg (SC)	12 % (RW) 23 % (SC)	
Brieger et al. (2021)	Recycling yard (one)	1,290 kg (C) 292 kg (HT)	21 % (C) 34 % (HT)	

residual waste collected from seven municipalities. Residual waste (RW) is defined as the waste discarded at the household in the mixed waste bin (Nørup et al., 2019). In addition to considering RW, Nørup et al. (2018) include textiles from the small combustible (SC) fraction, with each of the fractions coming from two different areas of Denmark. The SC fraction, by definition, should contain only waste that does not fit any of the recycling categories accepted at the recycling station and is collected in dedicated mixed waste containers placed at recycling stations (Nørup et al., 2019). Because most of the recycling centers in Denmark have separate containers for reusable textile, ideally, textiles for reuse should be sorted and placed in those containers. Furthermore, Brieger et al. (2021) analyze used textiles collected separately at a recycling yard in Germany, thus representing a higher volume and quality of collected textiles as compared to the other two studies. Even though this review is not exhaustive, the studies are representative and, to a certain extent, comparable, because they: 1) are published recently, 2) originated from Nordic/West European countries, and 3) used similar categories for sorting and elaborate on the sorting methods. The overall quality-related categories used in the studies are as follows: reusable, recyclable and waste. In addition, Watson et al. (2018) report the fractions as apartment waste (AW), which comes from apartments in multi-family housing, and house waste (HW), which comes from single-family houses. Nørup et al. (2018) divide the fractions between RW and SC. All three studies identify fractions composed of clothing and home textiles, thus separating out shoes, soft toys, and other textile accessories.

The reusable fraction contains products that can be reused in global markets as such (Watson et al., 2018) or with minor defects (Nørup et al., 2018). The definition of the recyclable fraction differs across the three studies. Common criteria are the condition of the textile and the fact that it cannot be reused, and the fiber composition. Nørup et al. (2018) additionally take into consideration the way a textile is produced (manufacturing method) and its size. Watson et al. (2018) sort the recyclable fraction into one fraction that can be used at existing recycling markets, such as industrial wipes (cotton based) and acryl/wool, and another fraction appropriate for upcoming/future recycling markets. This study (Watson et al., 2018) also presents higher volumes for recyclable textiles compared to the other studies, because the restrictions used for the reusable fraction were higher (see above). Furthermore, Nørup et al. (2018) categorized oil-based textiles as waste because their recyclability is also affected by their manufacturing method.

The waste fraction contains textiles that cannot be reused or recycled and must be incinerated. This is partly due to contaminated textiles but also because of the condition of the textile, the composition, and the manufacturing method. From these studies, it follows that the sorted quantities are highly dependent on the applied method and criteria for sorting, specifically where the lower limit for reusables and constraints for recyclables are set. Textile reuse should be favored and maximized in sorting, as in the case of Nørup et al. (2018), leading to a lower recycling fraction. Yet, the markets for low-quality reusable textiles are shrinking, making alternative treatments such as recycling more attractive.

No studies were identified concerning the potential recyclable volumes from the incinerated EOL textiles from public and private institutions. However, based on interviews, Dahlbo et al. (2021) find that most laundries were planning to redirect textiles from waste to recycling and provide examples of 50–97 % of EOL textiles being sent to recycling. Similarly, public institutions, such as police or customs, include textile recycling within their environmental strategy (2021–2032) to redirect uniforms from being incinerated (ibid.).

2.1.2. *Analytical approach to estimating volumes of recyclable textiles*

The volume of recyclable textiles is calculated as a sum of: 1) the estimate for the recyclable fraction from textiles that are incinerated, 2) textiles recycled in the country, and 3) textiles recycled abroad.

The values for the last two parameters are found in national studies of textile flows (Table 1), whereas the first parameter must be estimated by using the previous studies presented in Table 2. These studies report the recyclables in different categories: apartment waste (AW) and house waste (HW) in Watson et al. (2018), residual waste (RW) and small combustibles (SC) in Nørup et al. (2018), and clothing (C) and home textiles (HT) in Brieger et al. (2021). Each category represents a different proportion of the total clothing and home textiles. This requires converting them into a unified metric, defined as the fraction of recyclables (f_R) out of total clothing and home textile considering the weights of different categories ($W_{category}$):

$$f_{(R,\ Author)} = \left(W_{category1} {*} f_{Rcategory1} + W_{category2} {*} f_{Rcategory2}\right) / Total_{(clothing\ +\ home\ textile)} \quad (1)$$

To illustrate, for the study by Watson et al. (2018), the proportion of AW was approximately the same as the proportion of HW, such that the weight of each was $W_{AW} = W_{HW} = 168{*}0.5 = 84$ kg. The fraction of recyclable AW/HW (considering both existing and future recycling markets, Table 2) was, respectively, $f_{RAW} = 20.7\ \%+32.4\ \%=0.531$ and $f_{RHW} = 25.7\ \%+41\ \%=0.69$. Thus, the fraction of the recyclables can be calculated as follows:

$$f_{(R,Watson)} = (W_{AW}{*}f_{RAW} + W_{HW}{*}f_{RHW})/(W_{AW} + W_{HW}) = (84{*}0.531 + 84{*}0.691)/168 = 0.611 = 61.1\%$$

The same approach is applied in Nørup et al. (2018); however, here, the waste was analyzed in categories of RW (32.8 kg) and SC (276.6 kg), yielding a total (clothing and home textile) of 309.4 kg. The fraction of recyclables out of total clothing and home textiles in this study was calculated as $f_{(R,Nørup)} = 22\ \%$.

Considering the data provided by Brieger et al. (2021), the category of clothing was 1,290 kg, while the category of home textile was 292 kg, yielding a total of 1,582 kg. The fraction of recyclables out of total clothing and home textiles, after weighting the categories, was $f_{(R,\ Brieger)} = 23\ \%$.

Due to variety in the identified fractions, the authors of this paper decided to use a range of recyclable fractions with a minimum recyclable estimated volume of 23 % (complying with Brieger et al. (2021) and Nørup et al. (2018)) and a maximum estimated volume of 61 % (based on $f_{(R,\ Watson)}$). These fractions are multiplied with the household textile currently incinerated in each of the countries.

$$\text{Minimum recyclable estimated volume (households)} = 0.23{*}\text{Household textiles, incinerated} \quad (2)$$

$$\text{Maximum recyclable estimated volume (households)} = 0.61{*}\text{Household textiles, incinerated} \quad (3)$$

Based on the indications from the literature (Section 2.1.1), it is assumed that 50 % of the EOL textiles from public and private institutions that are incinerated will be recyclable in the near future.

Recyclable volume (public/private institutions) = 0.5*Textiles from public/private institutions, incinerated (4)

To summarize, the volume recyclable in each country is determined as follows:

$R_{c(Country)}$ = (0.23 or 0.61, respectively)*Textiles from household incinerated + 0.5* Textiles from public/private institutions, incinerated + Textiles recycled in the country + Textiles recycled abroad (5)

2.2. Estimating fiber composition of the recyclable EOL textiles

2.2.1. Data basis for analysis

The three reviewed studies use different categories of fibers, resulting in differing fractions. Nørup et al. (2018) group the compositions into three aggregated categories: natural fibers (such as cotton, wool, viscose), oil-based fibers (such as polyester, acrylic), and mixed fibers (a blend of natural and oil-based fibers). Their evaluation of the fiber content is mainly based on the clothing category because the composition of HT could not be exactly determined, resulting in a larger share of the recyclables being categorized as being of unknown origin. Due to this, Nørup et al. (2018) is not included in estimation of the fiber composition of the recyclables.

Based on the studies of Watson et al. (2018) and Brieger et al. (2021) the fractions for the following fiber compositions can be identified (summarized in Table 3): > 95 % cotton, > 95 % polyester, > 95 % viscose, > 95 % nylon, “mixed fibers/poly-cotton”, “natural fibers”, and “plastic fibers”. The last three categories were not specified further in those studies. Since “natural fibers” can be a very broad category, including plant and animal fibers, this is excluded from the further analysis. Mixed fibers likely include some mix of oil-based and natural fibers, though the proportion and composition of these has not been identified in the studies. Even though the “plastic fibers” category has not been further specified, it likely contains nylon and other synthetic fibers. Watson et al. (2018) identify that most of the recyclables for existing recycling markets (see Table 2) are cotton. For consistent comparison, it is not distinguished between fibers for existing and future recycling markets in Table 3 for Watson et al. (2018), but a total of both is considered. Both studies identify cotton fibers as the largest fraction, which does not reflect the fiber composition in terms of new textile production, in which polyester and other synthetics, dominate, followed by cotton. Each of the studies had one more fraction, leather (in Brieger et al., 2021) and wool/acryl sent for unravelling (in Watson et al., 2018), and these are not included in this study as not being of interest for F-to-F recycling.

To the authors’ knowledge, there are no studies on the fiber fractions of the incinerated EOL textiles from public and private institutions.

Table 3
Fiber-level fractions in EOL textiles from households, a synthesis of reviewed studies (AW – apartment waste; HW – house waste; C – clothing; HT – home textile).

Reference	> 95 % Cotton	Natural fibers	> 95 % Viscose	Mixed fibers	> 95 % Polyester	Synthetic fibers
Watson et al. (2018)	72 % AW 80.6 % HW		3.6 % AW 5.9 % HW	5.6 % AW 1.6 % HW (poly-cotton)	9.8 % AW 4.8 % HW	3.8 % AW 3.8 % HW (nylon)
Brieger et al. (2021)	39 % C 47 % HT	6 % C 5 % HT		35 % (C) 29 % (HT)	8 % C 13 % HT	10 % C 6 % HT (plastic fibers)

Regarding textiles from organizations that are currently recycled, Watson et al. (2018) find that about 55 % are cotton used for industrial wipers, and the remainder is wool/acryl that is unraveled in Asia.

2.2.2. Analytical approach to estimating fiber composition of recyclable textiles

Because the estimations of fiber compositions vary to some degree (Table 3), firstly, a weighted average is calculated for each fiber fraction within each of the two studies, followed by calculating the composite fiber fraction. Only for the viscose fraction was the calculation based on one study (Watson et al., 2018). When calculating the fiber fraction within each study, the above-presented method of weighting (Section 2.1.2) was applied. This is illustrated by the data from Watson et al. (2018) for the fraction of cotton in recyclables ($f_{Ct,R}$), which is calculated as follows:

$$f_{(Ct,R,Watson)} = (W_{AW}*f_{RAW}*f_{CtAW} + W_{HW}*f_{RHW}*f_{CtHW})/(W_{AW}*f_{RAW} + W_{HW}*f_{RHW}) = (84*0.531*0.72 + 84*0.691*0.806)/(84*0.531 + 84*0.691) = 78.9/102.6 = 0.77 = 77\%$$

Similarly, the fraction of cotton in recyclables in Brieger et al. (2021) can be calculated by calculating weighted fractions of clothing and home textiles, respectively, because this is how this study categorized the products in their analysis. Taking this into consideration, it follows:

$$f_{(Ct,R,Brieger)} = (W_C*f_{RC}*f_{CtC} + W_{HT}*f_{RHT}*f_{CtHT})/(W_C*f_{RC} + W_{HT}*f_{RHT}) = (1290*0.21*0.39 + 292*0.34*0.47)/(1290*0.21 + 292*0.34) = 152.3/370.18 = 0.41 = 41\%$$

The composite fraction of cotton in recyclables for both studies can be calculated by summing the weights of the respective categories and calculating the following:

$$f_{CtComp}=(78.9 + 152.3)/(102.6 + 370.18) = 0.49 = 49\ \%$$

Based on this method, the calculated composite fractions of fibers in household recyclables are 49 % cotton, 5 % viscose, 27 % mixed fibers, 9 % polyester, and 8 % synthetic fibers. Recalling the discussion in Section 2.2.1 on fiber fractions of incinerated textile from the public sector and currently recycled textile, this study assumes that the fraction distribution in these categories is the same as in household textiles. Assuming a cotton fraction of about 50 % in these categories is close to the findings of Watson et al. (2018), who report that about 55 % of currently recycled textiles are cotton used for industrial wipers.

2.3. Estimating the sorting and recycling capacity and balancing demand and supply

Interviews with relevant actors in four Nordic countries were carried out to estimate the sorting and recycling capacities, as well as discuss challenges related to collection, sorting, recycling, and enhancing circularity. The sampling logic obeyed a purposeful sampling procedure because this allowed selecting appropriate and suitable actors for a deeper understanding of recyclable EOL textiles (Eisenhardt, 1989; Eisenhardt and Graebner, 2007). The main actors included in the sample were collectors, sorting companies, and recycling companies, resulting in 43 interviews in total (Table 4). The interviewed collectors/NGOs were the biggest ones in the region, municipalities were those that were on the forefront of separate collection, while the selected automated

Table 4
Number of interviewees in terms of actor group and country.

	Municipality	NGO	Commercial collector	Sorting companies	Recycling companies
Denmark	2	3	1	1	1
Finland	3	2	4	1	1
Norway	2	4	1	1	1
Sweden	4	3	4	2	2
Total	11	12	10	5	5

sorting and F-to-F recycling companies were the ones that at that time were active and gave the researcher access. The interview data were complemented with organization-specific data captured via webpages or other material delivered by the interviewees. The interviews were held face to face or online, and in each interview, one or more researchers were present. The protocol included four categories of questions: collection (volumes collected, methods used, and logistics), product and process limitations (technology used, total capacity, and volumes processed), supply requirements (volumes imported and quality requirements), and circularity of recyclables (challenges and opportunities).

The estimated volumes of recyclables for each country were calculated using Equation (5), and fiber fractions per country were calculated by the percentages identified in 2.2. These were compared with a country's annual *capacity for automated sorting* and *annual capacity for recycling* to determine whether there is over-supply or free capacity in each country, as well as on a Nordic level.

2.4. Research quality

In general, the research using secondary data includes weaknesses, as the data was collected for another primary purpose than the purpose of this research. The earlier studies on textile flows used in this study reported difficulties in obtaining accurate data about the EOL textile volumes, because the textile flows are difficult to trace as large volumes are exported or incinerated (Watson et al., 2020a) and statistics are not complete. Thus, the secondary data contain assumptions, gaps, and uncertainties. Even though the data represents different years (2016 in Denmark and Sweden, 2018 in Norway, 2019 in Finland), this is the latest available data for each country. Another weakness of the secondary data was that rather small samples were used in the studies, they analyzed the EOL textile according to different categories, and missing sampling analyzes of incinerated volumes of public and private institutions' EOL textile and data on their flows.

To reduce these weaknesses and increase the reliability of the study, methodological considerations were made. The analytical method developed enabled combining different fractions by first identifying single fraction within one study followed by combined fractions across the studies, weighing the fractions with the weight of the sample studied. By considering several studies into a meta study, one gets more realistic estimations. Due to studies using different sources of EOL textile, partly differing criteria for sorting, and thus resulting with wider range of fractions, it was decided to estimate the minimum and maximum recyclable volume. The assumptions made for the fractions from public and private institutions were based on literature, and different categorizations were clearly defined through Sections 2.1 and 2.2.

The interviews data quality was ensured by the specific design and use of the interview protocol for the purpose of the study, by using the possibility to clarify the issues thought the interviews, by transcribing the interviews right after, and sharing the transcriptions with the involved participants to comment on the data.

3. Results

This section presents the results of the calculations and the interview study.

3.1. Supply of recyclable textiles in the Nordic countries

The estimated volumes of recyclable textiles (based on equation 5 and Table 1) and their fabric content (based on percentages identified in Section 2.2.2) in each of the studied countries can be seen in the upper part of Fig. 2. In total, the recyclable volume for the four countries is estimated to be between 70,600 and 140,500 tons. The large range of the estimation comes from the coefficients used when estimating the fraction of recyclables in the incinerated flow (as elaborated in 2.1.2), where the higher limit incorporates the fraction that can be mechanically recycled and sent to existing markets (wipers, for example). The highest supply volume of recyclables comes from cotton, mixed fibers, and polyester fibers, followed by other synthetic fibers (such as nylon), viscose fibers, and other (leather and fur).

Even though the potential recyclable volumes are quite large, the interviews show that recyclables are sorted out from the collected textile mass locally only to a small extent, but most are sorted only after the textiles have been exported. NGOs and commercial collectors explain that due to the low value of EOL textiles, combined with the high cost of manual sorting, the pre-sorting of recyclables is too costly in the Nordic countries. Due to the high costs, the interest towards the separate collection of recyclables is low, but cost compensation for pre-sorting or emerging technology for automated pre-sorting would change this situation. Due to the upcoming obligatory separate textile collection from households, ongoing pilots have indicated a significant increase in the volumes of collected recyclables. However, the lack of separate collection solutions, undeveloped regulation of collection and sorting methods, and lack of scale are, according to the interviews, the main barriers to increasing the level of recycling of EOL textiles. One recycling company explains that they prefer not to source from Asia and, instead, collects recyclables from 10 to 15 sites in Sweden, but they still have difficulties finding a sufficient supply of recyclables. Another recycling company stresses that, even though EOL textiles are free of charge, they are extremely expensive to collect, thus challenging the economic viability of the textile recycling industry.

3.2. Demand for recyclable textiles in the Nordic countries

The capacity and requirements for the incoming material among automatic sorting companies and recycling companies in the Nordics are presented in Table 5. Some of the actors are in an early or pilot phase, and the capacity indicated is what the company aims to reach when operating at full scale (indicating the year when this is planned). Most of the sorting companies accept non-reusable textiles that are clean and with removed hardware. One exception is NewRetex, which aims to accept any type of textile and automatically remove hardware. The largest recycling capacities are related to the chemical recycling of cellulose-rich fabrics (e.g. cotton and viscose). Only one recycling company is focusing on the chemical recycling of polyester and polycotton textiles. Another recycling company is developing recycling technology for any mix of polyester, plant-based (such as cotton, hemp), and manmade cellulosic fibers (viscose), and yet another is developing a solution for the mechanical recycling of wide range of fibers.

3.3. Balance between demand and supply of recyclable textiles in the Nordic countries

Considering the balance between the recyclables in each country and the respective sorting capacities (Fig. 1), it seems that Denmark, Finland, and Norway will have sufficient sorting capacity to deal with their potential recyclable volumes (maximum estimate), while the sorting capacity in Sweden will be lower than the local estimated volume of recyclables (maximum estimate). However, the upcoming sorting capacity in the Nordics will be sufficient to deal with the total recyclable fractions.

One of the organizations specialized in textile sorting stated that, to serve their customers, typically recycling companies, it is important to separate cotton, wool, other natural fibers, and pure polyester fibers into individual fractions and downcycle the remainder. Also, textiles should be clean and free of toxic chemicals, and hardware components, such as buttons and zippers, must be removed. Another sorting company claimed that the higher the requirements for sorting, the higher the sorting costs and the lower the margins. It typically requires several processing rounds to sort out the textiles to meet the quality

Table 5
The capacity (existing or full scale to be reached in the year indicated) and requirements of identified sorting and recycling (chemical (C) and mechanical (M)) facilities in the four Nordic countries.

Actor	Type of actor	Location	Supply requirement	Capacity (ton/year)
SIPTex	Sorting	Sweden	-Clean textiles,–No: hardware, multilayered material, longer than 2 *m*	24,000
Wargö Innovation	Sorting	Sweden	-Clean textiles	500–1,000
LSJH	Sorting	Finland	-Dry and clean, non-reusable, no paddings	65,000 for sorting
NewRetex	Sorting	Denmark	-Size limitations (not too large nor too small)	40,000 (2025)
NorSort	Sorting	Norway	-All textiles	60,000 (2023/24)
Infinited Fiber Company	Refining, (combined M and C)	Finland	-Cellulose-rich waste	30,000 of Infinna fiber in 2024
Renewcell	Recycling (C)	Sweden	−95 % cellulose content in each garment-Clean textiles-Hardware removed	Facility 1: 5,000 in 2022;Facility 2: 60,000 (initial), 120,000 total in 2023/2024
Södra	Recycling (C)	Sweden	−50–100 % white cotton mixed with polyester-Hardware removed-Clean textiles	2,000 (2022)25,000 (2025)
Textile Change	Recycling (combined M and C)	Denmark	-Any combination of polyester, plant-based, and/or manmade cellulosic fibers, including up to 15 % elastin-Clean textiles	15,000 (2023/2024)
Plast Nordic	Recycling (C)	Norway	-Polyester and polycotton textiles	30,000 (2024)
Rester	Recycling (M)	Finland	-Wide range of fibers (cotton, polyester, mixed, polypropylene, etc.)-Clean and sorted, from public/private sector	current capacity 12,000

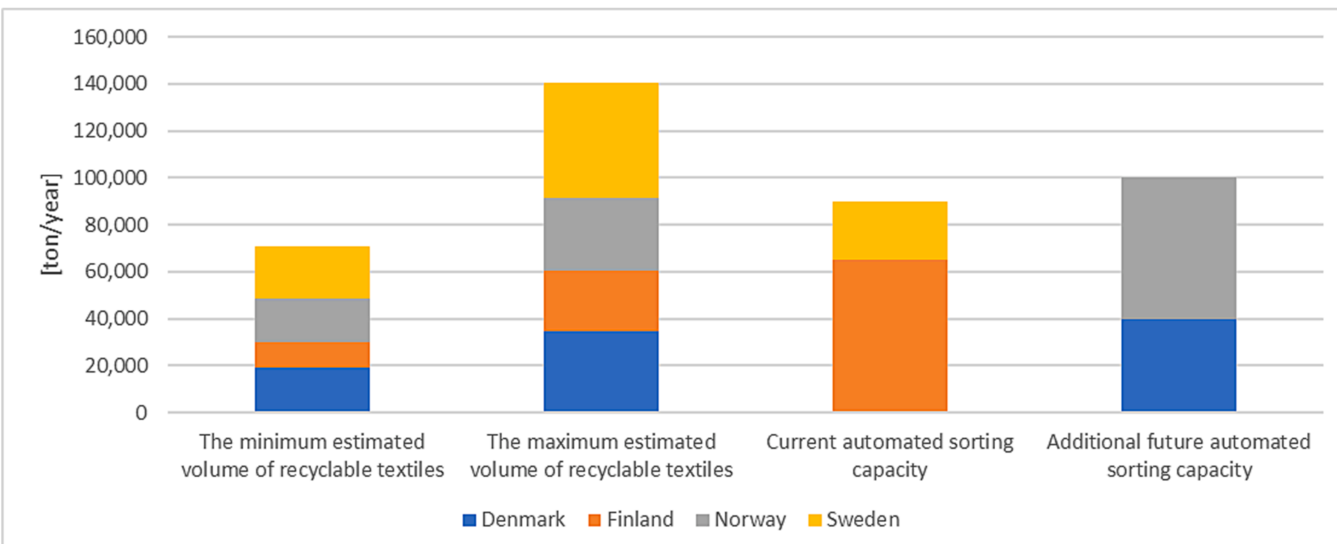

Fig. 1. The balance between the estimated supply of recyclable textiles and estimated sorting capacities in the four Nordic countries (tons/year).

requirements, but the positive effect is seen in the higher quality and value of the materials delivered. Due to these strict requirements, many recycling companies are sourcing from laundries that work with the private or public sector. The textiles they provide are expected to be more homogeneous in fiber content than textiles from households.

In terms of the fiber level balance of supply and capacity for F-to-F recycling, *currently existing* capacity (Table 5) is not sufficient to deal with the estimated (minimum) supply of recyclables. Fig. 2 presents the balance between the supply and demand of the expected upcoming recycling capacity within each of the countries, as well as at an aggregate Nordic level. The yellow fields indicate the over-supply of fibers, while the green fields indicate free capacity (after utilizing a country's own supply in the within-country analysis or after utilizing the Nordic level of supply in the Nordic-level analysis). To exemplify this, in the case of Finland, the maximum estimate of supply for cellulose-rich fibers is 14,091 tons (12,786 tons cotton + 1,305 tons viscose fibers) that can be recycled at a facility with 30,000 tons of capacity, thus resulting in a free capacity of 15,909 tons. In Fig. 2, it can be seen that all countries would have an over-supply (yellow fields) of synthetic fibers other than polyester. Denmark would have an over-supply of some of the fibers (cellulose-rich, polyester, or mixed fibers) since the upcoming recycling facility can process 86 % of the minimum estimated supply and 48 % of the maximum estimated supply of those three fiber fractions. Norway would have an over-supply of cellulose-rich fibers and some of the mixed fibers (polyester dominating mixes can be treated in Norway), and Sweden will have over-supply of polyester fibers. Finland and Sweden will have excess capacity to recycle cellulose-rich fibers, while Norway will have excess capacity to recycle polyester and polycotton fibers.

At an *aggregated Nordic level,* it is seen that the upcoming facilities for recycling polyester, cellulose-rich fibers, and mixed fibers will be sufficient to process all the estimated incoming fractions (maximum estimate). In fact, it is estimated that about 51 % of the capacity for the recycling of cellulose-rich and 58 % for the recycling of polyester fibers will require supply from outside the Nordics. There is a lack of capacity in the Nordics for recycling about 11,200 tons of synthetic fibers. Only one facility in Finland accepts polypropylene, but it is not clear what fraction of the synthetics supply this covers. Also, the fraction "others" must be investigated in more detail to understand the possibility for F-to-F recycling.

Various options for enhancing the recycling of textiles were brought up at the interviews. First, the sorting process needs innovations to become faster, more accurate, and automated. The composition of textile products needs to be transparent because, today, it represents a challenge for estimating the content and quality of the EOL textiles. Last,

	ESTIMATED SUPPLY						
	Recyclable fraction	**>95% Cotton**	**>95% Viscose**	**>95% Polyester**	**Mixed fibers**	**Synthetic fibers**	**Other**
Denmark	19,257 – 34,419	9,436 – 16,865	963 – 1,721	1,733 – 3,098	5,199 – 9,293	1,541 – 2,754	385 – 688
Finland	10,751 – 26,094	5,268 – 12,786	538 – 1,305	968 – 2,348	2,903 – 7,045	860 – 2,088	214 – 522
Norway	18,742 – 30,731	9,183 – 15,058	937 – 1,537	1,687 – 2,766	5,060 – 8,297	1,499 – 2,458	376 – 615
Sweden	21,862 – 49,222	10,712 – 24,119	1,093 – 2,461	1,968 – 4,430	5,903 – 13,290	1,749 – 3,938	437 – 984
Total	70,612 – 140,466	34,599 – 68,828	3,531 – 7,024	6,356 – 12,642	19,065 – 37,925	5,649 – 11,238	1,412 – 2,809

	UPCOMING DEMAND			
	Cellulose-rich	Polyester	Mixed fibers	Synthetic
Denmark	15,000			
Finland	30,000			
	12,000			Polypropylene
Norway		30,000		
Sweden	125,000		25,000	
Total	155,000+	30,000+	40,000+	

	SUPPLY – DEMAND BALANCE (within country)			
Denmark	2,331 – 15,977			1,541 – 2,754
Finland	15,909			
	2,607			<860 – 2,088
Norway	10,120 – 16,595	<27,234	<5,060 – 8,297	1,499 – 2,458
Sweden	98,420	1,968 – 4,430	>11,710	1,749 – 3,938

	SUPPLY-DEMAND BALANCE (Nordic level)			
	79,148	17,358	2,075	<11,238

Fig. 2. Estimated supply, demand, and balance between the estimated supply of recyclable textiles and total near future recycling capacities for different fibers in four Nordic countries (tons/year).

also the recycling technology must be improved to increase the tolerance levels for feedstock used in the processes, and several recycling companies are working to accept a more heterogeneous composition of textiles.

4. Discussion and conclusions

This study investigates the supply of recyclable textiles and the available capacity for automated textile sorting and F-to-F recycling in four Nordic countries. The study builds on earlier country-level studies (Dahlbo et al., 2021; SMED på uppdrag av Naturvårdsverket, 2018; SOU Statens Offentliga Utredingar, 2020; Watson et al., 2018; Watson et al., 2020b) and synthesises the volumes of recyclable textiles in the Nordics and their fiber composition. The study finds that, even though the level of the upcoming sorting capacity in the Nordics will be sufficient to deal with most of the total recyclable textile volumes, there is excessive recycling capacity for some fibers and a lack of capacity for others. The study identifies remarkable imbalances between demand and supply at the country level, which indicate opportunities for collaboration between the actors in the Nordic countries. This finding is in line with the identified need for ecosystems in the circular economy of textiles (Fontell and Heikkilä, 2017), but suggests collaboration in a specific geographical area, favoring local recycling solutions, instead of exporting. Therefore, this study creates knowledge about the circular economy of textiles and suggests that circularity challenges can be solved locally in the four countries this study examines.

Second, the study identifies the need to consider recyclable textile materials on a very granular level and thus serve the needs of recyclers. The sorting facilities must be able to deliver the exact desired textile fraction in sufficient volumes. In the context of textiles, considering material composition is needed, to understand the fine-grained balance between demand and supply. This finding adds to the challenges of textiles as a recyclable material; the materials are variable in quality and quantity and require advanced sorting solutions and knowledge about the demand to make textile circularity successful.

Third, the study shows that the circular flows must be analysed and understood from a supply chain management viewpoint to support balancing demand and supply for enabling economy of scale (Guide and van Wassenhove, 2009; Halldorsson et al., 2019). This study contributes to current knowledge on reverse supply chains for EOL textiles (Zhuraleva and Aminoff, 2021; Jäämaa and Kaipia, 2022). This is done by comparing supply volumes of recyclable materials with the available sorting and refining capacity, i.e. taking care of the recyclable textile volumes in an early supply chain phase. Also, as the supply and quality of materials may vary and require sorting and refining early in the reverse process to make the EOL textiles recyclable, this study investigates the balance point between demand and supply in an early supply chain phase. This balance point is needed to serve the demand of recyclable textile users and their specific requirements of raw material quality and content.

Fourth, it was found that the costs connected to logistics, especially, pre-sorting and sorting operations, are significant. Combined with textile-specific requirements, such as the need for the separation of fibers, dyes, hardware, and chemicals, the recycled textile materials are expensive compared to the use of virgin textile materials. To enhance the use of recyclable textile materials, incentives for the actors are needed, either on a national level or a Nordic level. Also, it is essential to engage the textile industry because textile design and choice of materials has a high potential to impact the costs of the sorting and recycling phases. In this regard, initiatives aimed at extended producer responsibility (EPR) are important.

In further research, the structure of the reverse flow and collaboration between textile collectors, sorters and recyclers in the Nordics deserves to be studied. This includes understanding of where the material flow shifts from push to pull triggers (de-coupling point) and how these flows can reach efficiency and sustainability. As technologies within automatic sorting and recycling are emerging, European recycled textile material may disrupt the entire textile industry. In further research it would be important to extend the focus of this study to other demand–supply balancing points and incorporate the fiber producers and textile industry. The demand from the fiber producers might drive the demand from the recycling companies and in turn the automatic sorting facilities. It is important to understand the pros and cons of different reverse logistics structures and design (centralized and decentralized) including all steps from collection to production. Related to this, there is a need to investigate new business models for recyclable flows to address the economic feasibility of actors. In addition, the supply of recyclable materials requires additional research; consumers and various organizations act as suppliers in reverse supply chains, and the supply of recyclable materials may be stochastic, variable, and unpredictable. Therefore, collection system design deserves attention in terms of mechanisms that make households and organizations separate the various textile fractions, which will have a remarkable impact on costly pre-sorting. Further research should also investigate the technology gaps in terms of the maturity levels of various technologies, such as chemical and mechanical recycling.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Secondary data was used. The sources are referenced in the paper

References:

Amicarelli, V., Bux, C., 2022. Quantifying textile streams and recycling prospects in Europe by material flow analysis. Environ. Impact Assess. Rev. 97, 106878 https://doi.org/10.1016/j.eiar.2022.106878.

V, Amicarelli, C, Bux., MP, Spinelli, G, Lagioia, Life cycle assessment to tackle the take-make-waste paradigm in the textiles production. Waste Management, 151 2022, 10–27. https://doi.org/10.1016/j.wasman.2022.07.032.

Baxter, J., Gram-Hanssen, I., Askham, C., Johanne, I., Hansen, B., Rubach, S., 2018. Exploring sustainability metrics for redesigned consumer products. J. Clean. Prod. 190, 128–136. https://www.sciencedirect.com/science/article/abs/pii/S0959652618311806.

I. M, Brieger, J.-P, Jarmer, M, Muschkiet, Coping with challenges of textile collection through an innovative framework towards a sustainable textile circular economy, 4th PLATE Virtual Conference, Limerick, Ireland, 26-28 May 2021.

Dahlbo, H., Aalto, K., Eskelinen, H., Salmenperä, H., 2017. Increasing textile circulation—Consequences and requirements. Sustainable Production and Consumption 9, 44–57. https://doi.org/10.1016/j.spc.2016.06.005.

H, Dahlbo, A, Rautiainen, H, Savolainen, P, Oksanen, P, Nurmi, M, Virta, O, Pokela, Textile flows in Finland 2019. Reports from Turku University of Applied Sciences 276. Turku: Turku University of Applied Sciences 2021. https://urn.fi/URN:NBN:fi-fe2021061738621.

Dubois, M., Sims, E., Moerman, T., Watson, D., Bauer, B., Bel, J.-B., Mehlhart, G., 2020. Guidance for separate collection of municipal waste. European Union. https://doi.org/10.2779/691513.

Eisenhardt, K.M., 1989. Building theories from case study research. Acad. Manag. Rev. 14 (4), 532–550.

Eisenhardt, K.M., Graebner, M.E., 2007. Theory building from cases: opportunities and challenges. Acad. Manag. J. 50 (1), 25–32.

Fleischmann, M., Krikke, H.R., Dekker, R., Flapper, S.D.P., 2000. A characterization oflogistics networks for product recovery. Omega 28, 653–666. https://doi.org/10.1016/S0305-0483(00)00022-0.

Fontell, P., Heikkilä, P., 2017. Model of circular business ecosystem for textiles. VTT Technical Research Centre of Finland. VTT Technology No. 313. https://publications.vtt.fi/pdf/technology/2017/T313.pdf.

D.V, Guide, L.N, van Wassenhove, The evolution of closed-loop supply chain research. Operations Research. Vol. 57, No. 1, January-February 2009, pp. 10-18.

Halldórsson, Á., Altuntas Vural, C., Wehner, J., 2019. Logistics service triad for household waste: consumers as co-producers of sustainability. Int. J. Phys. Distrib. Logist. Manag. 49 (4), 398–415. https://doi.org/10.1108/IJPDLM-02-2019-0065.

IVA, (2020). Textiles – from waste to resource by 2030. IVA. https://www.iva.se/globalassets/bilder/projekt/resurseffektivitet-och-cirkular-ekonomi/202002-iva-rece-branschrapport-textil-english-b.pdf.

Jäämaa, L., Kaipia, R., 2022. The first mile problem in the circular economy supply chains – Collecting recyclable textiles from consumers. Waste Manag. 141, 173–182. https://doi.org/10.1016/j.wasman.2022.01.012.

Jia, F., Yin, S., Chen, L., Chen, X., Mojica Herazo, J., 2020. The circular economy in the textile and apparel industry: a systematic literature review. J. Clean. Prod. 259, 120728.

Johnston, M.P., 2014. Secondary data analysis: a method of which the time has come. Qualitative and Quantitative Methods in Libraries 3, 619–626.

Koszewska, M., 2018. Circular economy - challenges for the textile and clothing industry. Autex Res. J. 337–347.

J, Lexén, C. L, Lindholm, L, Youhanan, Å, Stenmarck, (2016). SMED - Rekommendationer för utsortering av textilier med farliga ämnen ur kretsloppet. SMED Rapport Nr 175, 2016. Sveriges Meteorologiska och Hydrologiska Institut. www.smed.se.

Ljungkvist, H., Watson, D., Elander, M., 2018. Developments in global markets for used textiles and implications for reuse and recycling. Mistra Future Fashion report number 4.

S, Manshoven, M, Chrisris, M, Nicolau, E, Lafond, L. F, Mortensen, L, Coscieme, Textiles and the environment in a circular economy. Eionet Report- ETC/WMGE 2019/06. European Topic Centre Waste and Materials in a Green Economy. 2019 https://www.eionet.europa.eu/etcs/etc-wmge/.

McKinsey & Company, Apparel, Fashion and Luxury Group (2022). Scaling textile recycling in Europe – Turning waste into value. https://www.mckinsey.com/industries/retail/our-insights/scaling-textile-recycling-in-europe-turning-waste-into-value.

Nørup, N., Pihl, K., Damgaard, A., Scheutz, C., 2018. Development and testing of a sorting and quality assessment method for textile waste. Waste Manag. 79, 8–21. https://doi.org/10.1016/j.wasman.2018.07.008.

Nørup, N., Pihl, K., Damgaard, A., Scheutz, C., 2019. Quantity and quality of clothing and household textiles in the Danish household waste. Waste Manag. 87, 454–463. https://doi.org/10.1016/j.wasman.2019.02.020.

Palm, D., Elander, M., Watson, D., Kiørboe, N., Salmenperä, H., Dahlbo, H., Rubach, S., Hanssen, O.-J., Gíslason, S., Ingulfsvann, A.-S., Nystad, Ø., 2015. A nordic textile strategy Part II: a proposal for increased collection, sorting, reuse and recycling of textiles. TemaNord 2015, 513. , Nordic Council of Ministers. www.norden.org/en/publications.

Salmi, A., Kaipia, R., 2022. Implementing circular business models in the textile and clothing industry. J. Clean. Prod. 378, 1–9. https://doi.org/10.1016/j.jclepro.2022.134492.

G, Sandin, S, Roos, B, Spak, B, Zamani, G, Peters, Environmental assessment of Swedish clothing consumption - six garments , sustainable futures. Mistra Future Fashion report number: 2019:05, RISE. 2019.

Sandin, G., Peters, G.M., 2018. Environmental impact of textile reuse and recycling. J. Clean. Prod. 184, 353–365. https://doi.org/10.1016/j.jclepro.2018.02.266.

Sandvik, I.M., Stubbs, W., 2019. Circular fashion supply chain through textile-to-textile recycling. J. Fash. Mark. Manag. 23, 366–381. https://doi.org/10.1108/JFMM-04-2018-0058.

Schmidt, A., Watson, D., Roos, S., Askham, C., Brunn Poulsen, P., 2016. Gaining benefits from discarded textiles - LCA treatment pathways. TemaNord 537. , Nordic Council of Ministers. www.norden.org/nordpub.

SMED på uppdrag av Naturvårdsverket, (2018). Svenska textilflöden- textilflöden från välgörenhet och utvalda verksamheter. Rapport nummer 2. http://naturvardsverket.diva-portal.org/smash/get/diva2:1241255/FULLTEXT01.pdf.

SOU Statens Offentliga Utredingar, (2020). Producentansvar för textil - en del av den cirkulära ekonomin. SOU 2020:72, Miljödepartementet. https://www.regeringen.se/rattsliga-dokument/statens-offentliga-utredningar/2020/12/sou-202072/.

Textile Exchange, 2022. Preferred fiber and materials market report. https://textileexchange.org/wp-content/uploads/2022/10/Textile-Exchange_PFMR_2022.pdf.

Thorin, T., Johannessen, M., 2020. Textile flows and circular economy in Region Mid Jylland. RegionMidtJylland, Metabolic.

N, Tojo, B, Kogg, N, Kiørboe, B, Kjær, K, Aalto, Prevention of textile waste: Material flows of textiles in three Nordic countries and suggestions on policy instruments. TemaNord 2012:545 2012: Nordic Council of Ministers. http://dx.doi.org/10.6027/TN2012-545.

Watson, D., Trzepacz, S., Gravgaard Pedersen, O., 2018. Mapping of textile flows in Denmark. Danish EPA Environmental Project No. 2025, ISBN: 978-87-93710-48-1.

D, Watson, S, Trzepacz, N, Lander Svendsen, S, Wittus, N, Kiørboe, M, Elander, H, Ljungkvist, (2020a). Towards 2025: Separate collection and treatment of textiles in six EU countries. https://mst.dk/service/publikationer/publikationsarkiv/2020/jul/towards-2025-separate-collection-and-treatment-of-textiles-in-six-eu-countries/.

D, Watson, S, Trzepacz, S, Rubach, F. M, Johnsen, (2020b). Kartlegging av brukte tekstiler og tekstilavfall i Norge, https://norsus.no/en/publikasjon/kartlegging-av-brukte-tekstiler-og-tekstilavfall-i-norge/.

Zamani, B., Svanström, M., Peters, G., Rydberg, T., 2015. A carbon footprint of textile recycling: a case study in Sweden. J. Ind. Ecol. 19, 676–687.

Zhuravleva, A., Aminoff, A., 2021. Emerging partnerships between non-profit organizations and companies in reverse supply chains: enabling valorization of post-use textile. Int. J. Phys. Distrib. Logist. Manag. 51 (9), 978–998. https://doi.org/10.1108/IJPDLM-12-2020-0410.