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Identifying the potential for circularity of industrial textile waste generated within Swiss companies

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ABSTRACT

The textile industry is known to generate high amount of post-consumer waste that is generally landfilled or incinerated. In the era of circular economy, textile waste could be considered a resource to produce new textile products while reducing environmental impacts. While there are quite some studies on post-consumer waste, the industrial waste flows generated along different production steps of textile manufacturing have not yet been investigated. To fill this gap, this study collected quantitative data on industrial waste from Swiss companies. Based on a production of 15'880 tons, a total of 1505 tons of waste was generated in 2019. Out of this, 959 tons was made of yarn leftovers and 546 tons was made of fabric leftovers. Most of the yarn leftovers was made of one synthetic fiber (e.g. 100 % polyester), while most of the fabric waste was made of mixed materials. Incineration was the most used End-of-Life treatment with 562 tons, followed by reuse with 547 tons, open-loop recycling with 316 tons, and closed-loop recycling with 80 tons. The companies taking part in the study saw the biggest barrier to be the lack of market and of recyclers taking care of textile waste. The underlaying reason for this barrier is probably the fact that textile products are often made of mixed materials and recycling technology for these materials is not yet mature. If barriers were overcome, the 546 tons of waste fabric could potentially be used as raw material for manufacturing more than 1.7 million t-shirts.

1. Introduction

Until recently, waste was considered to be a product, material, or substance either no longer wanted or that cannot be used anymore. Its value is however currently changing thanks to the rise of Circular Economy (CE), which considers waste not as waste but on the contrary as a resource (Stahel, 2016; Tedesco and Montacchini, 2020). The idea behind CE is to reduce pressure put on non-renewable resources, reduce waste, and reduce environmental impacts due to production and consumption of products (Ashby, 2018; Kazancoglu et al., 2020). It can be applied either by promoting reuse and repair to extend products' service life, by minimizing waste, or by using waste as input material through recycling (Marques et al., 2020). Here, two recycling systems can be differentiated: open-loop recycling (the waste product will be processed and used in another value chain) and closed-loop recycling (the waste product will be processed and used within the same value chain) (Payne, 2015; Sandin and Peters, 2018).

In principle, any producing industry may have the potential to transition towards CE, which is for example the case for the textile industry being known for generating high amounts of waste (Niinimäki et al., 2020; Shirvanimoghaddam et al., 2020) and for its high environmental impact (Tukker et al., 2006). Both waste generation and environmental impacts happen throughout the entire life cycle of textile products including fiber, yarn and fabric production, dyeing and finishing, confection, distribution, use and end-of-life (EoL) (Niinimäki et al., 2020; Patti et al., 2021; Schmutz et al., 2021). Waste during manufacturing can take various forms including leftover of fibers, yarns, fabric scraps, etc. (Niinimäki et al., 2020; Patti et al., 2021), and edge trims and is commonly known as pre-consumer or industrial waste, while post-consumer waste is generated by consumers after use of their clothing items (Dobilaite et al., 2017; Sandvik and Stubbs, 2019). An alarming fact is that textile waste is continuously increasing due to an increased consumption linked on the one hand to low-cost fast fashion, decreased useful life and quality of clothing items, and on the other hand, to the growing population and expansion of the middle class (Koszewska, 2018). The total amount of waste could even reach 148 million tons worldwide by 2030 representing a 62 % increase compared to 2015 (The Boston Consulting Group, 2017). This represents a vast loss

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of resources as textile waste is currently mostly landfilled or incinerated (Dobilaite et al., 2017; Niinimäki et al., 2020). Both these EoL methods generate environmental impacts including release of methane and carbon dioxide in the atmosphere, and leakage of contaminants into soils (Patti et al., 2021).

In addition to the environmental impacts caused by pre- and post-consumer waste production, the manufacturing and use of textile products also raise certain environmental concerns. From the very first manufacturing step, fiber production has been shown to have diverse impacts depending on the used fiber type (Schmutz et al., 2021). For example, the most used fiber worldwide is polyester, accounting for 52 % of the total fiber production in 2019 with approximately 57 million mt (Textile Exchange, 2020). Polyester, as well as other synthetic fibers (e.g. polyamide/nylon), are made from non-renewable resources and require a high amount of energy for their extrusion (Payne, 2015). Moreover, questions have been raised concerning the release of microplastics into the environment and more particularly to the oceans. Conventional cotton is the most used natural fiber reaching 25.7 million mt (Textile Exchange, 2020). Pesticides, fertilizers and artificial irrigation are required for its production (Kooistra and Termorshuizen, 2006), which consequently has an impact on its carbon and water footprints (Schmutz et al., 2021). However, fiber production is not alone in contributing to environmental impact. Other manufacturing steps such as the dyeing and finishing, as well as yarn production are highly energy intensive (Schmutz et al., 2021). The dyeing and finishing step has also raised some environmental concerns due to the heavy use of chemicals (Roos and Peters, 2015).

Considering the various environmental impacts and waste amounts caused by the production and consumption of clothing items, making a transition towards a circular textile economy could help mitigate them (Koszewska, 2018). Many studies have already focused on this subject, including research on the valorization of textile waste (Barla et al., 2018; Patti et al., 2021; Shirvanimoghaddam et al., 2020; Stanescu, 2021; To et al., 2019), on the challenges and barriers of transitioning towards a circular textile economy (Franco, 2017; Hole and Hole, 2020; Kazancoglu et al., 2020; Koszewska, 2018; Luján-Ornelas et al., 2020; Saha et al., 2021; Sandvik and Stubbs, 2019), on current sustainable practices in the textile industry (Islam et al., 2020; Jia et al., 2020), on recycling technologies (Payne, 2015; Piribauer and Bartl, 2019) and on the environmental impacts or benefits of textile reuse and/or recycling (Bamonti et al., 2018; Braun et al., 2021; Koligkioni et al., 2018; Liu et al., 2020; Sandin and Peters, 2018; Shen et al., 2010; Subramanian et al., 2020; Woolridge et al., 2006; Zamani et al., 2015). Others analyzed the material flows of post-consumer textile waste at regional or national levels including countries such as Australia (Moazzem et al., 2021), Finland (Dahlbo et al., 2017; Virtanen et al., 2019) and Denmark (Koligkioni et al., 2018; Nørup et al., 2019). Finally, only one study has focused on material flows of pre-consumer textile waste by analyzing the waste generated at three Lithuanian sewing companies during clothing confection (Dobilaite et al., 2017).

Even though the transition towards a circular textile industry has been studied to some extent, to our knowledge no study has investigated the waste flows generated along different production steps of textile manufacturing other than confection, and non that includes the form of waste, its material composition and current waste management.

This knowledge is essential for the implementation of circular waste management strategies (Dobilaite et al., 2017). Hence, to fill this gap, this study aims at analyzing the waste flows generated within Swiss textile companies as pre-consumer waste. The composition and quality of this waste is well known. This could be a starting point to identify potentials for circularity. In Switzerland, in contrast to the EU, there is still no legislative pressure to avoid or recycle textile production waste, but only those wastes for which there is no environmentally compatible process for their disposal[1]. Nonetheless, Switzerland was selected because of the high interest and engagement of the textile industry and the public agencies in making the textile industry more sustainable and circular, This is demonstrated by the Swiss sustainable textiles initiative[2] and the Swiss-charta for sustainable textiles (IP Kerenzerberg, 2019). In addition, Swiss textile companies develop products of high quality and high functionality, providing an opportunity to explore the potential circularity of waste.

To do so, quantitative data from Swiss companies on industrial waste was collected through a questionnaire, followed by a data verification via phone interview. After collection, data were aggregated for the material flow analysis (MFA) from production to waste management following a categorization by forms and materials. In addition to waste flows data, information regarding barriers linked to recycling were collected. The results are then discussed in the context of the waste hierarchy (European Commission, 2008), showing the challenges, barriers, needs and possibilities for the waste regarding waste minimization, reuse and recycling. Finally, a discussion regarding the potential for waste.

2. Methods

2.1. Data Collection

In order to analyze waste flows generated within Swiss textile companies, a questionnaire was sent via e-mail by the Swiss Textiles association[3] in January 2020 to their members (72 companies having production plants in Switzerland). The questionnaire was divided into four section: 1) General information including roles of companies in the textile value chain, 2) Production of textile products (e.g. yarn, fabric) and respective material composition, 3) Type of waste produced (e.g. leftover of yarn, fabric, fabric edge), and 4) Waste management.

Regarding the production of textile products, participants had to fill in a table according to some product categories. A product category was defined as *one or more products that have the same material composition (e.g. all yarns made of 100 % cotton or fabrics made of 50 % cotton and 50 % polyester). For example, in case two fabrics have different colors or finishing but have the same material composition, these two fabrics are part of the same product category*. For the five most relevant product categories (in terms of weight), the production amount (in tons) in 2019 and the material composition had to be reported.

For the textile waste, another table had to be filled in according to waste categories. One waste category was defined as *a waste made of a specific form (e.g. yarn leftovers, fabric leftovers, or edge trims)*. For each waste category, information about their respective amount in tons, and the percentage of trims, accessories, or defaults had to be provided. Two additional questions were included in this section. One about possible ways to reuse/recycle the waste and the other about why it is difficult to recycle or reuse textile waste.

In the last section about waste management, the management of the different waste categories had to be reported. Four options were given for the waste management: (1) incineration, (2) reuse, (3) closed-loop recycling, and (4) open-loop recycling. Landfill was not given as an option as there is no landfilling in Switzerland. Reuse was defined as *the reuse of a waste category in the same form and function (i.e. without mechanical or chemical treatment), and* recycling as *waste category that is mechanically or chemically treated/recycled.* Recycling can be "open-loop"

[1] Environmental Protection Act, EPA) of 7 October 1983 (Status as of 1 January 2021 (https://www.fedlex.admin.ch/eli/cc/1984/1122_1122_1122/en)

[2] https://www.sts2030.ch/

[3] https://www.swisstextiles.ch/en/

– meaning that the *waste is used in another value chain* (e.g. construction buildings) – or can be "closed-loop" – meaning that *waste is used as raw material within the same value chain (in the textile industry)*. In addition, in this section, two other questions were asked. The first about the costs of disposal (e.g. for incineration and recycling), and the second about the measures taken for reducing waste.

After receiving data from companies and performing a consistency check, phone interviews were planned in order to verify and clarify some of the data. Moreover, during the phone interviews, information regarding the reasons for waste generation was gathered.

2.2. Material Flow Analysis

After collecting data, a material flow analysis (Brunner and Rechberger, 2016) was performed in order to understand the flows of textile waste according to their form and material composition. The system boundaries can be seen in Fig. 1. The different products and wastes of the various companies were aggregated according to their product type and according to their waste type. The products were grouped into two categories: yarns and fabrics. Yarns included filament yarns, yarns, cords, and ropes, while fabrics included knitted and woven fabrics, raw (greige) fabrics and finished fabrics. Waste was grouped into four categories: yarn leftovers, raw fabric leftovers, fabric leftovers, and edge trims. The difference between raw fabric and fabric leftovers is that the raw fabric is not dyed and finished yet. The edge trims represent the cuts of textile fabrics' edges generated during their manufacturing. These categories were selected based on the answers provided by the textile companies.

In the questionnaire, the material composition was asked only for the products and not for the waste itself. The reason behind this decision is that companies know their products well but have less information about the material composition of their wastes. They do however have information about the amount of waste per waste category. Thus, the material composition of the waste was determined by using the same proportion as those of the products.

Some companies gave the amount of waste for fabrics and edge trims at the same time (under one waste category). To separate the waste in two categories, the weight of edge trims waste and of fabric waste were estimated from the ratio of other companies that gave these wastes as two separated waste categories. It was estimated that the edge trims represented 23 % of the total waste coming from fabric production.

2.3. Data Representativeness

In Switzerland, there are no data about the amounts of textile production within the country. Therefore, in order to evaluate the representativeness of the collected data, the turnover of companies (hereafter companies turnover) who participated in the study was compared to the total turnover of companies in that same field. The total turnover could be calculated by using NOGA codes[4] (General Classification of Economic Activities), which are presented in Table 1. All the companies participating in the study are registered in one of these categories.

For the companies' turnover, data were retrieved from the Swiss Textile association database. For some companies, the turnover was not available. In that case, the turnover of other similar companies was used for the estimation based on production volume and corresponding turnover or directly taken from the company's website if available.

3. Results

3.1. Roles of companies participating in the study and their representativeness in the Swiss and European market

In total, 14 Swiss textile companies participated to the study. However, one company was excluded because – though it was a Swiss company – the production was not based in Switzerland and thus was out of our scope. Most of the companies are active in more than one role in the textile value chain. All the steps of the value chain are represented: "Dyeing and Finishing" was the most represented role (7 companies out of 13), followed by "Fabric production" (6 companies), "Yarn/Cords/Ropes production" (5 companies), and "Fiber production" (3 companies). Some companies also had some activities in the confection sector, even though no waste from this sector was reported in the questionnaire, likely because located outside of Switzerland.

In order to have a first impression of the representativeness of these 13 companies in the Swiss market, we summed up the companies' turnover and compared it to the total turnover in Switzerland (taken from the previously mentioned NOGA codes presented in Table 1). The study companies' turnover was equivalent to almost 700 Mio CHF and the total turnover was equivalent to a bit more than 1 billion CHF, thus representing 69 % of the Swiss market. In comparison, the total turnover in Europe in 2018 for Textile and Clothing branch corresponded to 154.5 billion Euros[5].

3.2. Material used for textile products

Different materials were used by the companies for the manufacture of textile products, as can be seen in Fig. 2.

The synthetic fiber materials included polyester (PES), polyamide (PA), polypropylene (PP), elastane (EL), polyurethane (PU), and Polytetrafluoroethylene (PTFE), while the natural fibers included cotton (CO), wool (WO), and Flax (FL). Two additional materials of cellulosic origins were used, which are viscose (VS) and micromodal (MCD). Finally, steel and natural latex (LA) were also used in some products. The total production of both yarn and fabric products was equivalent to 15'880 tons. As can be noticed in Fig. 2, PES is the most used material, accounting for 64 % of the total production, followed by PA (11 %), PP (10 %), and CO (6 %), showing that synthetic fibers are more prominent than natural fibers. A small amount was of unknown exact material composition (2 %). For this share, information regarding whether the products were of synthetic or natural origin were given, but the exact used materials were not mentioned.

3.3. Material Flow Analysis

The results of the MFA can be seen in Fig. 3. For each compartment, the relative amounts of materials are shown within a pie chart and are aggregated into three categories: products/wastes made either of one synthetic fiber in yellow (e.g. 100 % PES), of one natural fiber in light blue (e.g. 100 % CO), or of mixed fibers in dark blue.

<u>Products</u>

Beginning with yarn and fabric products (first row), it can be seen that more yarn products (11′508 tons) was produced than fabric products (4′372 tons) in 2019, even though the number of companies producing yarns or fibers is lower than the number of companies producing fabrics and taking care of the dyeing and finishing step. Most of the yarn products are made of one synthetic fiber (89 %), while for fabric products the picture is different: half is made of one synthetic fiber, 35 % of mixed fibers and 15 % made of one natural fiber.

<u>Waste</u>

Even though most of the products are sold or exported (14′375 tons),

4 www.bfs.admin.ch/bfs/de/home/statistiken/industrie-dienstleistungen/nomenklaturen/noga/tool-unterstuetzung-noga-codierung-kubb.html

5 EURATEX-Facts-Key-Figures-2020-LQ.pdf

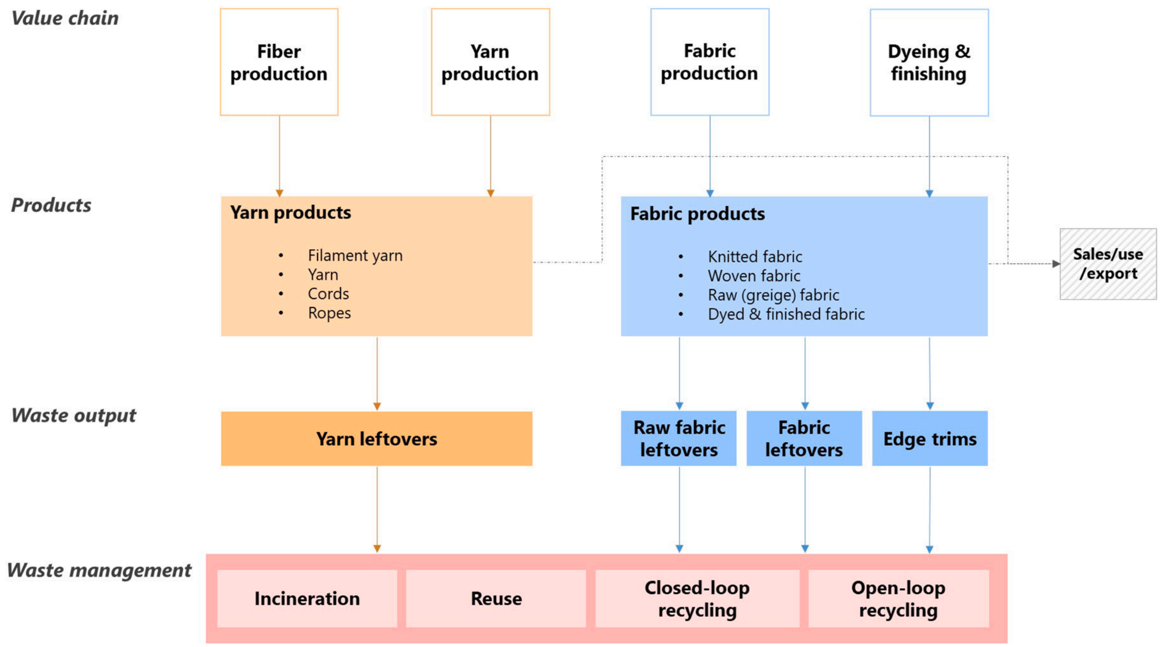

Fig. 1. Study system boundaries for the year 2019. The waste is generated by Swiss textile companies. The MFA considers only the production waste at the factory and not the waste after leaving the factory (waste in stores, waste after use, etc.), which is shown in the grey box.

Table 1
NOGA codes used for calculating the total turnover.

NOGA codes	Name
131	Preparation and spinning of textile fibres
132	Weaving of textiles
133	Finishing of textiles
1394	Manufacture of cordage, rope, twine and netting
2060	Manufacture of man-made fibers

8 % and 12 % of waste is generated during the manufacturing of yarn and fabric products, respectively. As for the yarn product, the yarn leftovers (959 tons) is mostly made of one synthetic fiber and the remaining of mixed fibers.

For the fabric waste (i.e. raw fabric leftovers, fabric leftovers, and edge trims), it can be noticed that the highest amount of waste goes for the fabric leftovers, with 409 tons, followed by edge trims with 128 tons and raw fabric leftovers with 9 tons. On the one hand, for both fabric leftovers and edge trims, most of the waste is made of mixed fibers (68 %), showing a change of tendency compared to the fabric products

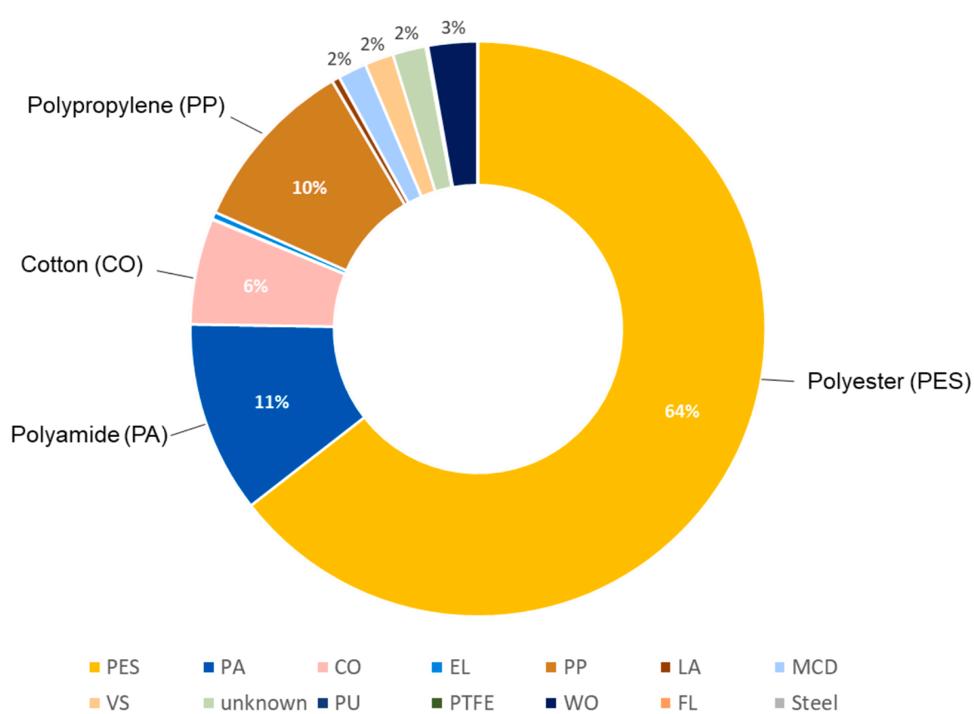

Fig. 2. Relative amount of material used in the textile products' manufacturing (all products confounded).

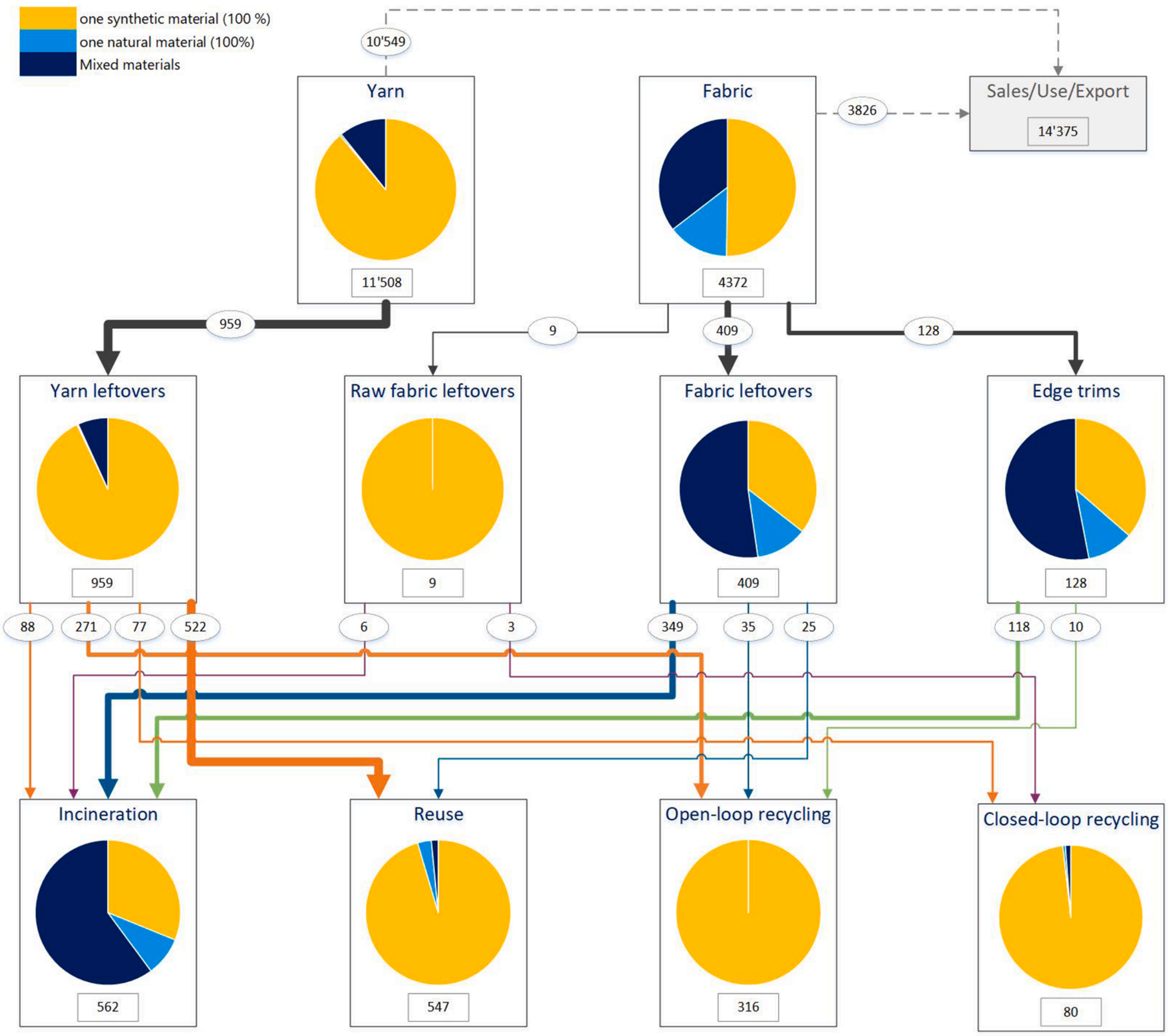

Fig. 3. Material Flow Analysis of textile waste generated within Swiss companies. The first row represents the products, the second the waste type, and the third the waste management. Each product, waste and waste management option is presented in a separated compartment. The arrows represent the flows of materials. For each flow and each compartment, the tons of material is provided (number in the ovals and in the squares, respectively). The flows from the yarn leftovers to the different waste management options are represented with orange arrows, those of raw fabric leftovers in violet, those of fabric leftovers in blue, and those of edge trims in green. The arrows have different sizes showing the importance of the flows in terms of weight in tons. Each compartment contains a pie chart showing the relative amounts of products/wastes made either of one synthetic material (in yellow), of one natural material (in light blue), of a mix of materials (dark blue).

which had 35 % of mixed materials. It seems therefore that the use of mixed fibers – during fabric manufacturing – produces more waste than if only one fiber is used (synthetic or natural). On the other hand, the raw fabric waste is only made of synthetic fibers.

Waste management

Different waste management options have been used, as can be seen in Fig. 3, with incineration currently being the most common one (562 tons). Reuse comes in a second position with 547 tons, open-loop recycling as third with 316 tons, and lastly closed-loop recycling with 80 tons.

The biggest flow comes from the yarn leftovers that goes to reuse (522 tons), making up for almost the entire amount of waste ending up in this waste management option, showing that only few fabric wastes use this option. Open-loop recycling is also often used for treating yarn leftovers (271 tons), but less incineration (88 tons) and even less closed-loop recycling (77 tons). From the total yarn leftovers, only 9 % goes to incineration, while 91 % is reused or recycled.

The picture is different for the three fabric wastes, where 86 % ends up incinerated. From 409 tons of fabric leftovers, 349 tons go to incineration, 35 tons are recycled in an open-loop and 25 tons are reused, but none is recycled in a closed-loop. Most of the edge trims are incinerated (118 tons) and only a small amount is recycled in an open-loop (10 tons). Closed-loop recycling is only used (from the fabric wastes) for the raw fabric leftovers, though only to a small extent (3 tons).

When considering the material composition of the various waste management options, it can be seen that for the incineration, most of the waste is made of mixed materials (60 %) and is followed by waste made of one synthetic fiber (31 %) and by waste of one natural fiber (9 %). This is not surprising as the majority of the waste that goes to incineration comes from fabric waste, which is mainly made of mixed fibers. Another aspect to point out is that waste made of one natural material is mostly incinerated (74 %). For the three other waste management options, the waste is primarily made of one synthetic material (from 95 % to 100 % depending on the option).

For a detailed overview of the materials used within the waste and how these are treated at their end-of-life, refer to the Supplementary Material.

3.4. Reasons for waste generation and waste mitigation

Now that the waste flows have been identified, it would be interesting to understand why the waste is generated in the first place. This question was asked during the phone interviews, and the summarized answers are found below.

Some of the yarn and fabric waste is inherent to the manufacturing of textile. To produce a fabric, yarns wrapped around some cones are used, and for the machine producing the fabric to function correctly, a certain tension is needed. This tension cannot however be maintained when the yarn is almost at its end. Thus, a small amount of yarn is left on the cones, ending up as waste. Edge trims are another example of waste that is inherent to textile manufacturing and is produced during the weaving of fabrics and after fabric finishing.

In some cases, mistakes during the manufacturing of yarn or fabric can happen, for example when the raw material is of bad quality, when the yarn is not correctly wrapped on the cones in the first place, or when the machine does not have the right settings. In addition, it was mentioned that the color of a fabric may vary slightly between two different batches, which may not fulfill the expectation of a designer. In that case entire rolls of fabric may be wasted.

Three further reasons for leftover generation were pointed out. The first is that in some cases, yarns or fabrics have to be ordered in larger amounts than needed because suppliers only sell large quantities of raw materials. The second reason is that orders to suppliers must be made in advance, in order to have the material in storage and be able to quickly answer the client's demand. However, a client's order may never come, or they may order smaller quantities, thus also leading to waste generation. If orders to suppliers were made on demand, the client would need to wait before getting his merchandise and this is something that most clients are not prepared to agree to. The third reason being that sometimes, a collection cannot be completely sold before it reaches its end.

In the questionnaire, a question about how waste could be mitigated was asked and the five following answers were given: (1) the production processes should be continuously optimized, (2) new adapted technologies should be used, (3) the raw materials should be of better quality, (4) the tolerance and awareness of clients and designers should be increased, and (5) working on commissions would avoid unnecessary leftovers (which is not always possible, as mentioned above).

3.5. Challenges to waste recycling

Textile companies mentioned that there were many challenges to be overcome in order to move towards a circular economy. As we have seen in Fig. 3, recycling is still less common than incineration (especially for fabric wastes). This is due to various factors, as presented in Fig. 4. The most common challenge among companies is that there is no market and no recycler taking care of textile waste. It was mentioned during the interviews that previously the waste could be sent to China (e.g. synthetic edge trims) and Africa (e.g. rolls of fabric). However, this is no longer the case, and as it appears that no one within Switzerland is interested in taking back the waste, companies have no other choice than to give it for incineration.

The second biggest challenge seems to be that the required recycling technologies are not yet available. Some companies mentioned that the technologies are missing for mixed materials and for textile products that have different layers, which are glued together. In addition, some finishing chemicals make the fabric so soft that it can no longer be recycled in an open-loop, for example by using fabric rolls to transform it into cleaning rags.

Two challenges about the amount of waste were raised, which are that the amount of waste is not always constant (i.e., it varies throughout the year) and that there are too small amounts per waste category. This renders textile waste less attractive for recycling companies, which need

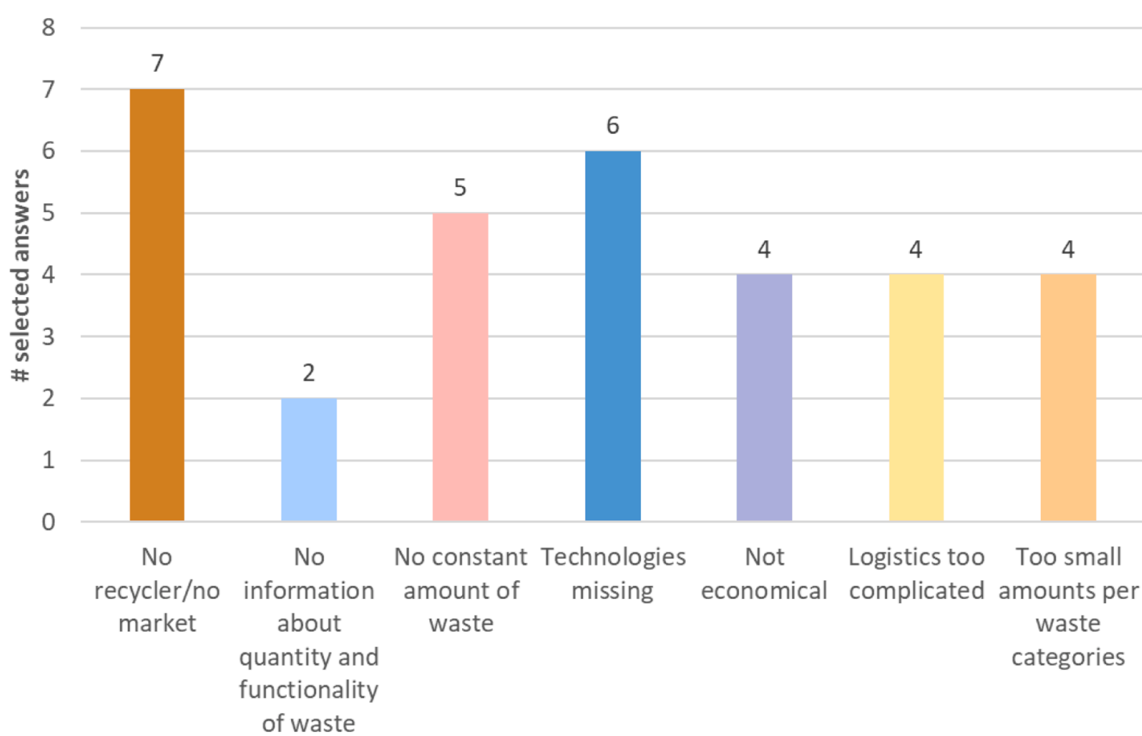

Fig. 4. Challenges to textile recycling.

certain volumes to make a business case.

Some companies brought forward that currently recycling was not economically sound, because recycling is more expensive than incineration. It was also mentioned that using waste is more expensive than producing new products made in China for example. In addition, clients and users seem to be more attracted to new and cheap products than to products originated from waste that are more expensive (though of high quality). In the questionnaire, data regarding costs of waste elimination was also recorded and it was found that the amount paid by companies varies greatly, ranging from 0.005 CHF/ton to 300 CHF/ton. On average the price for incineration is 154 CHF/ton, suggesting that the price of recycling should be lower than this to be economically viable.

Logistics also raise some concerns. Some companies have many different types of products, made of different mixes of materials and with different colors, thus sorting the waste would involve intensive efforts.

Lastly, it seems that the information about quantity and functionality of waste is less relevant than the other above-mentioned challenges.

4. Discussion

4.1. Waste flows and the waste hierarchy

As we have seen with the MFA, 1505 tons of waste were generated from a production of 11′508 tons. These data are unique and no other studies to the authors knowledge have analyzed similar data. Dobilaite et al. (2017) focused on industrial textile waste and, in particular, waste generated in three Lithuanian factories during garment manufacturing. Therefore, their results cannot be directly compared with ours. However, they found that most of the waste consists of mixed materials, which is similar to our results.

According to the waste hierarchy (following the 4Rs principle) (European Commission, 2008), waste should be first reduced, reused, recycled, and then recovered (energetically, i.e. from incineration plants). However, from the MFA we can see that incineration was the most common EoL treatment with 562 tons, thus not in line with the sustainability ladder. Reuse came second, and was often used for yarn wastes (522 tons), while this was much less the case for fabric wastes (25 tons). A similar picture was found for the open-loop (271 tons of yarn, respectively 35 tons of fabric waste) and closed-loop (77 resp. 3 tons) recycling treatments, which came as third and fourth waste management options, respectively. Hence, at least for the fabric wastes, much improvement could be done to increase the ratio of waste going to reuse and recycling, and ultimately to enhance their circularity. In the following paragraphs, the possibilities and challenges of waste minimization, reuse and recycling are discussed.

4.2. Possibilities and challenges for waste minimization

As just mentioned, before choosing between reuse and recycling, mitigating waste should be the first priority (European Commission, 2008). In the sub-chapter 3.4 "Reasons for waste generation", the results show that waste can be inherent to the production, can originate from mistakes, or can happen because of some external reasons, which generate leftovers. To reduce waste, some possible options were mentioned by companies: (1) optimize the production processes, (2) use new adapted technologies, (3) use better quality of raw materials, (4) increase the tolerance of clients and designer, and (5) work on commissions. For the latter, we have seen that working on commissions may not be advantageous as companies have to react quickly to the client's demand, and if they cannot offer a quick response, they would likely lose their clients to their competitors. So, unless clients are becoming more tolerant regarding the time lapse between the moment they ordered a product and the time they receive the merchandize, working on commission will stay unattractive to many companies. A possible way to change this situation, may be by increasing the awareness of clients and inform them about the waste that is generated and that could be avoided. Another possibility, but rather idealistic, would be that all competing companies work on commission. However, this currently seems unrealistic.

In the same logic, the awareness of designers about waste mitigation could be increased. Indeed, designers have some power over the amount of waste that is generated during the manufacturing of fabrics, for example during the dyeing and finishing step. As we have seen above (sub-chapter 3.4), there may be small variations of color between different batches. If these small differences would be accepted by designers, but also probably by consumers, much waste could be avoided. Generally, designers have an important role to play in the transition towards a circular economy, as during the design step, many decisions are made (e.g. choice of material, choice of color, simple vs more complicated design, etc.), which will later on have an influence on the amount of waste generated and the recyclability of textile products (Sandvik and Stubbs, 2019). However, the different choices a designer may take and how it will influence the sustainability and circularity of textiles is beyond the scope of this study.

The three first above-mentioned options to mitigate waste (i.e. production processes optimization, use of new adapted technologies, and use of better quality of raw materials), are more of a technical nature. To the authors' knowledge, there is almost no scientific literature addressing waste mitigation during the manufacturing of textile products. Only one paper could be found focusing on the reduction of waste during the confection of a striped t-shirt (Vilumsone-Nemes et al., 2020) (though confection was not part of the scope of this present study), showing a need for further investigations on how best to mitigate waste at production sites.

4.3. Possibilities and challenges for reuse

For the waste that cannot be avoided and mitigated, ways should be found to reuse and then recycle it, as both were shown to be environmentally advantageous (especially reuse), compared to landfill and incineration (Sandin and Peters, 2018). From Figure 3, we can see that 547 tons of waste was reused, out of which 522 tons coming from the yarn leftovers, which shows that reusing yarn leftovers is easier than reusing fabric waste. The reason for this may be that yarn leftovers can be reused again within the same company in their own production plant, or that it could be sold somewhere else. Fabric wastes are more complex products, and this may explain why it is also more difficult to reuse them. However, there is still the possibility to increase reuse of fabrics by putting in place an (online) shop that could sell good quality leftovers from products for the general public. This idea has already been implemented by a few companies, but at the same time was abandoned by others as the efforts involved were too high. Not only could the fabric be sold but also edge trims (from knitted fabric), which are increasingly often used by knitters and are already being sold by brands such as Hoooked[6]. Unfortunately, no scientific literature could be found regarding possibilities on how to increase reuse of pre-consumer waste, showing a gap that should be further investigated. Studies on reuse usually focus on post-consumer waste and ways to increase the service life of clothes (e.g. Shirvanimoghaddam et al., 2020).

4.4. Possibilities and challenges for recycling

Following the principles of circular economy, textile waste going to incineration (here 562 tons) could instead be used as raw material within the same value chain (closed-loop recycling) or in another one (open-loop recycling). Currently, from the MFA results, it seems easier to recycle in an open-loop than in a closed-loop. It can be also be seen that for both waste management options the textile waste is made of one

[6] https://www.hoookedyarn.com/en/

synthetic fiber, while for the incineration the waste is mainly made of mixed materials. This goes in line with what is discussed in the literature about the fact that the recycling of mixed materials is currently still difficult (Jia et al., 2020; Payne, 2015; Piribauer and Bartl, 2019; To et al., 2019). This was also mentioned by the Swiss companies (subchapter 3.5) that no technologies are nowadays ready for mixed materials and that no recyclers (in Switzerland) are interested yet in taking back textile waste. For the moment, mechanical recycling seems to be the most used technology, though usually used for textiles made of one fiber (e.g. 100 % CO or 100 % PES). For example, mechanical recycling was used to recycle a circular polyester jacket, and this process was environmentally beneficial when comparing it with a "linear" jacket (Braun et al., 2021). It should however be noted that with mechanical recycling, the quality of the fiber decreases, meaning that the addition of some virgin material to the recycled product in order to achieve a product of high enough quality is often necessary (Niinimäki et al., 2020). Another recycling technology that is often referred to in the literature is chemical recycling (also mainly used on single materials). The advantage of chemical recycling over mechanical recycling is that the recycled fiber can achieve almost the same quality as virgin materials (Payne, 2015; Sandin and Peters, 2018). Unfortunately, this technique is not yet used at industrial scale (it is still on lab or pilot scale) and needs further development (FOEN, 2017; Girn et al., 2019). Since mechanical and chemical recycling techniques are still mostly used on mono-materials, solutions should be found for mixed materials. One solution could simply be to avoid mixed materials whenever possible, though not always feasible as blends can provide enhanced functionalities appreciated by consumers (e.g. higher quality, breathability, etc.) compared to mono-fibers (Sandvik and Stubbs 2019). For those textiles that cannot avoid blends, new recycling technologies must then be developed. One of the most promising technologies for mixed materials seems to be the use of biochemical processes, which are highly selective and environmentally friendly (Piribauer and Bartl, 2019).

Swiss companies also mentioned further challenges towards recycling, which are the inconsistent amount of waste generated throughout the year, the too small amount of waste per waste categories, and the complicated logistics (see Fig. 4). According to Hole and Hole (2020), the collection and sorting should be a priority and this even before improving recycling technologies. A possible way to overcome these barriers could be by creating synergies among companies and by collaborating with recycling companies. Instead of having separate flows of waste for each company, the waste could be collected in a centralized way, for example, which would potentially enable achieving interesting amounts for recycling companies on the one hand and simplify the logistics for companies on the other hand. By collaborating, the question about the necessary amount and how the waste should be sorted could be determined. More specifically, should the waste be pre-sorted by the companies and then sent to recyclers? Or should sorting be taken care of by a centralized company? These are still open questions to be investigated, though it was suggested that sorting waste should already happen during the production phase according to their materials (Patti et al., 2021). There are other questions yet to be answered: what is the recyclability of the different materials and their possible recycling loops (closed and open-loop)? Which of these loops are the most appropriate and the most environmentally friendly? These are important questions and we should be aware that circularity may not always be the most environmentally friendly solution, as in some cases incineration with energy recovery might be preferable over recycling (Islam et al., 2020).

A last challenge mentioned by companies was regarding the currently non-economical aspect of recycling. Financial constraints was found in the literature to be one of the major barriers for circular economy (Jia et al., 2020; Ülgen and Forslund, 2015) and should therefore also be considered. For the companies which are incinerating their waste, it was shown earlier that the average price was 154 CHF/ton, suggesting that the price of recycling should be lower than that to be economically attractive. Additionally, the price of recycled fibers should be made more attractive to be able to compete with cheaper virgin materials of the same quality. No study was found in the literature that addressed the cost ranges of recycling. Further research on this topic would therefore be interesting to better understand the profitability of recycling for companies. Table 2 presents a summary of the above-mentioned challenges/barriers to recycling and their respective needs.

Table 2
Barriers/challenges towards recycling and corresponding needs.

BARRIERS/CHALLENGES	MITIGATION STRATEGIES
1.No market and no recycler	• Creation of collaborations with recycling companies
2.Missing recycling technologies	• Identification and evaluation of recyclability of materials, of possible recycling loops and potential use of textile waste in other sectors • Further development of recycling technologies (especially for mixed materials) • Avoid mixed materials when possible
3.Amount of waste is not constant	• Creation of synergies among companies
4.Too small amount per category waste	• Creation of collaborations with recycling companies
5.Complicated logistics	• Centralized collection enabling achieving interesting amounts for recycling companies
6.Not economical	• Price of recycling should be competitive with those of incineration • Price of recycled materials should be competitive with those of new raw materials of the same quality

4.5. Potential of textile waste

We have seen with the MFA that a total of 1505 tons of waste (959 tons of yarn waste and 546 tons of fabric waste) could potentially be collected. This amount may even be higher taking into consideration that not all Swiss textile companies participated in the study and that confection waste was not included in the study. But in order to give a first impression of what this amount could represent we could take the number of t-shirts that could be made out of fabric waste (the majority of yarn waste stems from technical yarns and is mostly reused). To estimate this, we needed the recycling efficiency and the number of fibers needed for manufacturing one t-shirt:

- For the efficiency, we considered an efficiency of 85 % (i.e. 15% of the mass is lost) reported for mechanical polyester recycling (from the fabric to the fiber) in Braun et al. (2021).
- For the fiber mass requirements, we assumed 264 g of fibers, which are needed for manufacturing a t-shirt of 154 g (average weight) as described in Schmutz, Hischier, and Som (2021). The losses of mass happens at each step of the manufacturing of a T-shirt. For more details, please refer to the study from Schmutz, Hischier, and Som (2021).

Thus, by assuming that all 546 tons of fabric waste can be recycled (even those made of mixed materials), 1′757′955 t-shirts could be produced (See Supplementary Material for the calculations). Even though this number shows an ideal case, it illustrates the potential of recycling if the technologies would be able to deal with mixed materials and if the t-shirts were made of 100 % recycled fibers, which is currentlynot yet the case due to quality loss.

Compared to post-consumer waste, the data collected here is relatively small. The waste collected in 2019 reached 55,400 tons in

Switzerland[7]. A 2012 study[8] analyzing the composition of Swiss citizens' waste bags found that about 3% (by weight) of textiles ends up in waste bags, resulting in about 50,000 tons of clothing in household waste.

4.6. Limitations

For this study, it was assumed that the material composition of the waste was proportionally the same as that of the products in order to simplify the data collection for companies and keep their efforts low. It is therefore possible that the material composition of the wastes does not represent the exact reality. However, as mentioned above, some of the waste is an inherent part of the textile manufacturing process (e.g., edge trims), and it is likely that this waste is similar for any type of material composition. To get a more precise figure of the material composition of waste, data could be collected and directly monitored at the production site while waste is being generated. This would provide accurate figures, although the effort would be really high.

In addition, the proportion of waste depending on their cause (discussed in section 3.4) has not been collected. This could be interesting in a further study to investigate this, in order to be able to gain more insight in the topic of textile waste and provide more concrete measures for mitigating textile production waste in the future.

5. Conclusion

This study has provided new and exclusive quantitative insights about the waste flows of pre-consumer textile waste generated within Swiss companies according to the waste forms and material types. Furthermore, it sheds light on the reasons why waste is generated in the first place and the barriers faced by companies to move towards a more circular textile industry. The current situation of pre-consumer textile waste in Switzerland could be ameliorated as high amounts of textile waste of high quality and well-known composition is going to incineration, thus not being in line with the circular economy. To change this situation, on the one hand, collaborations among textile companies and recyclers are necessary to bring enough materials together and define best ways for the sorting of textiles. Without such collaborations, the full potential of textile waste is hampered. On the other hand, further development of recycling technologies is needed as well as research on recyclability of materials and the sustainability of successive recycling loops. Finally, the quantitative insights regarding waste flows could provide a robust basis for potential recyclers to evaluate business opportunities.

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Author contributions

Conceptualization, M.S and C.S; methodology, M.S and C.S.; formal analysis, M.S..; investigation, M.S.; data curation M.S and C.S.; writing—original draft preparation, M.S.; writing—review and editing, M. S. and C.S.; visualization, M.S.; supervision, C.S..; project administration, C.S.; funding acquisition, C.S. All authors have read and agreed to the published version of the manuscript.

[7] Abfallstatistiken (admin.ch)

[8] erhebung_der_kehrichtzusammensetzung2012.pdf

CRediT authorship contribution statement

Mélanie Schmutz: Investigation, Methodology, Conceptualization, Formal analysis, Supervision, Data curation, Writing – original draft, Visualization, Writing – review & editing. **Claudia Som:** Project administration, Methodology, Conceptualization, Formal analysis, Funding acquisition, Visualization, Writing – original draft.

Declaration of Competing Interest

The authors declare no conflict of interest.

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Supplementary materials

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