Recycling technologies for enabling sustainability transitions of the fashion industry: status quo and avenues for increasing post-consumer waste recycling

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ABSTRACT
A major environmental issue of the rise in garment production is a steep increase of textile waste. At the same time, recycling technologies appear to be promising avenues for sustainability transitions of the fashion industry. This article examines the chances and challenges of scaling recycling technologies for textiles and considers the collection and sorting processes as well as the actual reuse. Drawing on case studies and expert interviews, the results indicate current obstacles and opportunities for accelerating diffusion of recycling technologies. Various initiatives are promising, however industry structures, garment designs, and business models need to be re-orientated and re-aligned to accelerate these recycling concepts. Applying the greenwashing notion that acknowledges co-creation by producers and consumers, the article critically argues that the focus on recycled polyester bottles for garments distorts incentives to improve other recycling technologies and masks the true cost of textile-waste recycling. Instead, fashion-brand companies and retailers should leverage their market power to foster sustainability standards in the global recycling industry.

ARTICLE HISTORY
Received 18 May 2021
Accepted 5 January 2022

KEYWORDS
Apparel; garment; recycling; sustainability; textile; used clothes

Introduction
The sizeable increase in garment production over the last decades has generated several benefits in terms of social and economic sustainability. The benefits include economic growth and employment opportunities in low- and middle-income countries, raising the income of many households (Mottaleb and Kalirajan 2014; Uddin 2014; Olds 2009) and expanding availability of affordable garments for low-income households (Taplin 2014). The vast growth, however, has brought enormous negative impacts for the environment and also considerable social costs (Niinimaki et al. 2020). The quest for better environmental practices along the whole life cycle from fiber production to garment disposal and higher labor standards, including living wages and adequate health and safety measures, attests to the downsides of these developments (Biadgo et al. 2021; Steinisch et al. 2013; Peters, Li, and Lenzen 2021).

Transforming the textile and garment sector toward a full-spectrum approach to sustainability will require phasing out and substituting unsustainable manufacturing practices. Among the environmental issues, with increasing fashion consumption on a global scale, textile waste is becoming a particularly difficult and growing problem (Sandin and Peters 2018; Shirvanimoghaddam et al. 2020). This challenge includes industrial waste such as fibers, yarn, fabric, garment remnants, unsold stock from rejects and overproduction, and post-consumer waste of worn garments. Sustainability transformation as a deliberate socio-technical transition entails both social transformation and technical innovation as well as broad diffusion of sustainable solutions (O’Brien 2018; Geels 2019). While global fiber production has almost tripled from 1975 to 2018 (EEA 2021), many European brands doubled their fashion release from 2001 to 2011 (Remy, Speelman, and Swartz 2016). At the same time, clothing prices dropped in Europe by approximately 30% when corrected for inflation and European textile consumption is estimated to be 26 kilograms (kg) per person (EEA 2021). The COVID-19 pandemic lowered fashion consumption only in its early stages, with brands responding with heavy discounts and purchase incentives that in due course drove sales back up again (Brydges, Retamal, and Hanlon 2020; Dowsett 2020).
Garments fulfill several functions beyond protecting bodies from the environment. Fashion, in particular, serves to express status and identity (Crane 2000). The fashion industry is built to continuously reinvent and to provide an increasing number of products (Taplin 2014). With slowly reducing poverty worldwide (UNDP and OPHI 2020), and with ethical fashion, slow fashion, and reduced consumption in fashion being only niche phenomena confined mainly to industrialized countries (Joergens 2006; Vladimirova 2021), we can expect a continuing increase in garment production and consumption accompanied by an increase in textile waste in coming decades.

A promising approach for tackling textile waste is recycling. This includes mechanical recycling but also chemical and novel biological recycling technologies of blended fiber-textile products (Navone et al. 2020; Sanchis-Sebastià et al. 2021; Sandin and Peters 2018). The objective of this article is to contribute to an understanding of the status quo and prospects of recycling for sustainability transitions in the fashion industry by posing the following questions: What are the challenges and chances to increase recycling of garment waste considering the whole process from collecting to actual recycling? Considering the role of consumers, fashion businesses, and collecting and sorting companies, the findings identify specific issues associated with recycling approaches along each stage of the value chain.

The history of technology provides many examples of innovation that aimed to solve one environmental problem and ended up creating another, or came with unexpected and undesirable side effects. A prominent example is the cultivation of agricultural crops for renewable biofuels that adversely impair biodiversity and wildlife (Jager and Kreig 2018). Another instance is sharing-economy concepts such as shared use of automobiles. Instead of reducing overall car dependency, there are indications that the practice leads to additive consumption, discouraging users from more sustainable transportation modes such as bicycles and public transport (Amatuni et al. 2020). Accordingly, this article aims to provide a critical view that also focuses on the drawbacks and downsides of some practices in the fashion- and textile-recycling sector and investigates whether some practices may be little more than greenwashing.

The concepts of circular economy and, in particular, the related notions of closed and open loops, waste streams and recycling, and greenwashing as a co-produced process among fashion brands and consumers are the main concepts used in the analytical part of this article. The study complements a thorough process of desk research on recycling with qualitative and empirical research: case studies of businesses that conduct recycling of worn garments and expert interviews. The desk research and analysis drew mainly on information and other data pertaining to the textile-waste and recycling situation in Europe. However, the recycling industry is globalized due to used clothes exports for sorting and for secondhand markets. The insights from case studies and expert interviews with representatives of European business and research institutes confirm how the recycling business is part of global value chains. Accordingly, the findings are also relevant to some extent to recycling industries outside of Europe.

**Recycling as a circular economy avenue for sustainability transitions of the fashion industry**

With non-governmental organizations (NGOs) such as the Ellen McArthur Foundation claiming the fashion industry to be a highly polluting industrial sector (e.g., EMF 2017), many top-down initiatives from policy and bottom-up from industry and NGOs have started over the last two decades to trigger sustainability transitions. Policies have focused on supply-chain responsibility, environmental issues, and waste treatment; notable examples are the European Union’s (EU) waste directive that requires member states to collect textile waste as a separate waste stream starting in 2025 and the Circular Economy Action Plan to increase reuse, recycling, and circular design (Jacometti 2019). In addition, industry and NGOs have developed certification systems to create and demonstrate sustainable supply chains (including codes of conduct), formulated plans to reduce overproduction, and launched efforts to improve design for longevity and recyc-

lability (e.g., Brydges, Retamal, and Hanlon 2020; Vladimirova 2021). A promising approach is the extension of the length of the use phase of garments (RISE 2019). However, a longer use phase still does not address the problem of the growing amount of textile waste from overproduction and increasing consumption. Accordingly, politicians and industry representatives consider recycling to be an important part of sustainability transitions of the fashion industry (Sandin and Peters 2018).

A concept with increasing popularity to govern sustainability transitions on a policy and on a firm level is the circular economy (EEA 2021; EMF 2017; van Bahr et al. 2019). After a short introduction to waste streams and recycling processes, this article turns its attention to how circular economy approaches can contribute to converting waste into
new resources through different recycling methods. To provide the basis of a critical view on recycling, the concept of greenwashing as a co-creation process is described.

**Types of waste and recycling in the fashion industry**

In Europe, the overflowing garment-collection containers during the COVID-19 pandemic brought the textile-waste issue to public attention. Donations increased tremendously, while charity shops could not open to resell secondhand garments (Wearn 2021). The situation also revealed the global interconnectedness of textile-waste streams. Shipments from Europe to African and Asian countries paused during the pandemic, leaving collectors with increased warehouse costs (Bauck 2020).

Textile waste from the fashion industry can be categorized into industrial waste, pre-consumer waste, and post-consumer waste (Wang 2006). First, industrial waste occurs during manufacturing of fibers, yarns, fabrics, and garments. This includes fibers unsuitable for yarns due to length or coarseness, remnants, trimmings, and cutoffs during fabric and garment processing, as well as scraps associated with unmet quality standards. The fiber composition, processing chemicals, dyes, and finishes of industrial waste are usually known, which makes it a better fit for recycling.

Second, pre-consumer waste includes unsold stock and returns in stationary and online sales. Some industry specialists consider unsold stock and returns to also be an industrial waste as the fashion industry is responsible for accurate disposal. According to the EU waste directive (EC 2018), waste should be avoided by any means and can only be discarded in landfills when the products cannot be used anymore. However, according to the German Federal Ministry of Environment, accurate figures on the amount of unsold stock and returns and the type of disposal of these garments are not known in Europe, as brands do not provide these kinds of information (GFME 2019). The garments often contain multi-fiber compositions, prints, buttons, zippers, and trimmings. Outdoor apparel may contain waterproof membranes, coatings, and water repellents. In some countries, products such as curtains and baby clothes, flame-retardant finishes are required (Figure 1).

Finally, post-consumer textile waste contains worn garments and household textiles. These items end up in domestic trash bins or get donated. As used textiles are not considered hazardous waste with special waste-treatment requirements, they are typically not collected by municipalities but by private firms and charities (Weber, Lynes, and Young 2017). In the EU, consumers discard about 11 kg of textile waste per person per year (EEA 2021). The majority of these materials are incinerated or end up in landfills. A smaller percentage is resold as secondhand garments in Europe or shipped to other countries and sold on secondhand markets. Recent figures show that the EU exported about 1.5 million tons of worn clothing to Asian and African countries in 2018 (Manshoven et al. 2019). Secondhand clothes are also critically discussed by politicians, economists, and NGO representatives. They argue that the large amounts of used clothes that arrive at Asian and African secondhand markets undermine local garment industries (Brooks and Simon 2012).

Only a few countries, such as Germany, have structured textile-waste collection and recycling facilities (Manshoven et al. 2019). Shirvanimoghadam et al. (2020) estimate that worldwide two-thirds of this material is disposed in landfills and only 15% of textile waste— including pre-consumer and industrial waste—is recycled. Another part of the textile-waste stream gets incinerated in cogeneration facilities used to produce electricity or heat (Schmidt et al. 2016). As synthetic fabrics involve the use of crude oil as a constituent of their manufacture, their properties for energy generation (namely their limiting oxygen index) is better than brown coal that continues to be widely used in some parts of Europe and elsewhere. Although thermal recovery is sometimes included in recycling, in this article it is not considered in recycling methods for textile waste.

The textile waste that gets recycled is usually industrial waste and to a smaller extent post-consumer, domestic waste. Recycling methods are usually distinguished according to the type of process: mechanical, thermal-mechanical, chemical, and biological (Chavan 2014; Robinson 2020). First, mechanical recycling is the most important textile-recycling treatment in terms of quantities. It is also the preprocess for the other three recycling
technologies. While some researchers (see, e.g., Sandin and Peters 2018) prefer classifications based on the level of disassembly of the recovered material, the distinction according to recycling method is insightful as it reflects the different phases of technological and industry development and the current state of industrial application of these recycling processes (Table 1).

Mechanical recycling is as old as garments because producing new fibers and yarns was traditionally more time consuming than recycling existing textiles. For example, during the late Middle Ages cotton waste became so valuable for paper manufacturing as book printing increased that governments imposed bans on textile-waste exports and cotton cloth became a profitable trafficked good (Craig 2019). As new fiber production became over the centuries more expensive than recycling, mechanical recycling came to be established all over the world and has been continuously improved to efficiently generate fibers for non-wovens and for new fabrics. This development started to slow down with the increase of affordable synthetic fibers in the 1990s.

A typical mechanical recycling product is wiping rags, which are fabric squares cut from mainly cellulose fibers. The price for wiping rags is higher than rags, which are fabric squares cut from mainly cellulose fibers such as cotton and viscose and synthetic fibers like polyester. This recycling method involves disentangling the fibers from fabrics through cutting, ripping, and carding. As the fiber properties deteriorate due to the harsh treatment, only about 5% gets used for new yarns in combination with virgin fibers for new wovens and knits for garment and the majority gets processed into non-wovens (Palme 2017; Wang 2006).

Second, thermal-mechanical recycling refers to processing fibers into granulate for melt spinning. This is only possible for synthetic fibers which can be extruded through this technique. As fibers from the garment industry are often contaminated with additives such as pigments, ultraviolet stabilizers, and flame retardants, the industrial manufacturing of recycled polyester draws mainly on polyester bottles from food packaging as raw material (Chavan 2014; Sandin and Peters 2018). Many brands such as Adidas and H&M are committed to fully replacing virgin polyester with recycled polyester (rPET or recycled polyethylene terephthalate) over the next few years. Accordingly, they strongly advertise the use of rPET which is usually made from used plastic bottles from the food industry as they contain significantly less foreign additives and pigments than polyester garments (Bussé and Van Krijsdijk 2019; Piribauer and Bartl 2019). While the majority of bottles and other plastic packaging is locally recycled – countries such as Norway, Sweden, Japan, and India achieve recycling rates of more than 80% (Tiseo 2020) – the majority of PET fiber-manufacturing plants are based in China which has a low national recycling rate and banned imports of plastic waste (d’Ambrières 2019).

Third, chemical recycling is possible for both cellulose fibers such as cotton and viscose and synthetic fibers like polyester. This recycling method breaks down fibers into polymers, oligomers, and monomers which are then used as feedstock for new human-made fibers (Robinson 2020; Sanchis-Sebastiá et al. 2021; Wang 2006). An example of

| Recycling technologies | Product examples | Advantages | Limitations |
|------------------------|------------------|------------|-------------|
| Thermal recycling      | Energy, heat     | No fiber sorting, suitable for all types of waste | Using exhaust-gas treatment, only synthetics have good limiting oxygen index |
| Mechanical recycling   | Wiping rags, yarns for new fabrics, fabric strips for blankets Nonwovens for insulation mats | All fibers and fiber mixtures Processes readily established Closed and open-loop recycling | Mechanical cutting and ripping of textiles may deteriorate fiber properties High-quality yarns require additional virgin fibers |
| Thermal-mechanical recycling | Polyester yarns out of Polyester bottles | High-quality fibers and yarns similar to virgin polyester fibers Open-loop recycling | Homogenous fiber inputs Better suited for industrial waste |
| Chemical recycling using chemicals to break up fibers | Cellulosic oligomers and polymers out of worn cotton and other cellulose fibers, polyester monomers, oligomers out of polyester | High-quality fibers and yarns equivalent to virgin fibers Suitable for closed-loop recycling | Homogenous fiber inputs Better suited for industrial waste |
| Biological recycling using enzymes to break up fibers | Cellulosic oligomers and polymers out of cotton and other cellulose fibers, polyester monomers, oligomers out of polyester | High-quality fibers and yarns equivalent to virgin fibers Suitable for closed-loop recycling | Homogenous fiber inputs, Better suited for industrial waste |

Table 1. Recycling technologies in the textile industry.
chemical recycling of cellulosic fibers is the Refibra® technology from the Austrian company Lenzing, which uses a certain percentage of industrial waste cotton as feedstock (Palme 2017). Chemical recycling of polyester has been done on an industrial scale for more than a decade by the Japanese company Teijin (Teijin Frontier, Ltd 2021). The Swedish start-up Renewcell recycles cotton-polyester blends (Renewcell 2021). Chemical recycling is less widespread due to its higher investment costs, skill requirements, and processing costs. The low cost for virgin fibers especially has to date made chemical recycling of polyester on an industrial scale less attractive (Kumar and Joshiba 2020).

Finally, a novel method for handling certain fabrics is biological recycling. Similar to chemical recycling, the fibers are broken down into short polymers, oligomers, and monomers (Navone et al. 2020). The cellulosic fibers are processed with cellulase enzymes and synthetics with enzymes that can hydrolyze the synthetic fibers (Piribauer and Bartl 2019). At present, biological recycling is still only operationalized on a laboratory scale and industrial applications remain to be developed in the future.

Circular economy: open- and closed-loop recycling

Politicians, NGO representatives, and scientists alike consider circular economy business models to be a key element for sustainability transitions of the fashion industry (van Bahr et al. 2019; Pal 2017). Circular economy approaches call for the 6Rs: reduce, redesign, reuse, recover, remanufacture, and recycle (Malek and Desai 2019) for addressing the environmental impact of the production and disposal of fashion items. The current collection and recycling systems are limited to reducing the production of new items by the reuse of used clothes through secondhand markets and to recycle new garments and other textile products.

Circular economy recycling concepts can be designed as closed loops or open loops. The notion of a closed loop refers to processes in which materials are kept in a loop for applications involving the same products (Palme 2017). An example is the recycling of polyester workwear by Teijin that produces new polyester fibers for the garment industry (Teijin Frontier, Ltd 2021). Other examples from the fashion industry include cotton-denim trousers which can be returned to fashion enterprises that then distribute it further to recycling businesses; through mechanical recycling the fibers can be spun into new yarns and woven into new fabrics for denim trousers. Open loop refers to products that are made of materials from other sectors and products that are recycled for other applications. An example of open-loop recycling is rPET from beverage bottles that are remanufactured into polyester fibers for garments (Park and Kim 2014).

As open-loop recycling can result in less valuable products such as wiping rags or nonwovens for insulation mattings, it is sometimes regarded as a form of downcycling and hence a less attractive alternative (Piribauer and Bartl 2019; Sandin and Peters 2018). But open-loop systems can also incorporate upcycling. Polyester bottles that are upgraded from food packaging to garments are an example of effective upcycling (Palme 2017; Park and Kim 2014).

Greenwashing as co-creation of producers and consumers

The term “greenwashing” was initially coined to refer to practices whereby businesses provide false information about the environmental performance of their products and technologies (Laufer 2003). These dubious activities typically include marketing strategies that aim to improve a company’s ecological appearance through the use of trademarks, certifications, and product names that reference terms such as “green,” “eco,” and “bio.” These claims are not generally legally protected even though trademark law in most European countries prohibits wrong and misleading product information. With the rise of corporate social responsibility (CSR) and sustainability reporting during the 1990s, the term greenwashing was extended to firms that provided erroneous or deceptive information about their sustainability activities (Laufer 2003; Ramus and Montiel 2005). The current understanding of greenwashing judges business communication more strictly by including exaggeration of sustainability activities, vague claims, and misleading imaginaries that suggest environmentally friendly activities to gain market shares and competitive advantage (Dahl 2010; Delmas and Burbano 2011). Accordingly, greenwashing includes clear cases of fraudulent communication as well as subtler, suggestive, and disingenuous information (de Jong et al. 2020).

This conceptualization is challenged by Seele and Gatti (2017) who argue that information can be misinterpreted by consumers and other organizations, especially when business communications contribute to exaggerated expectations by consumers. Seele and Gatti (2017, 239) define greenwashing as “co-creation of an external accusation toward an organization with regard to presenting a misleading green message.” The concept of co-creation is consistent with communication theories that postulate that the meaning of artifacts and concepts cannot be
considered without the shaping of the receiver (Torelli, Balluchi, and Lazzini 2020). Accordingly, some accounts of greenwashing may even be unintentional (de Jong et al. 2020). However, the responsibility for accuracy of sustainability claims remains with the sponsoring businesses and should not be imposed on the consumers.

Humanitarian and environmental organizations, NGOs, and others have sharply criticized the fashion industry in recent years for polluting the environment and perpetuating disastrous work conditions including child labor and modern slavery (Clean Cloth Campaign 2021; EMF 2017; Greenpeace 2021). Public attention and industry activities and policies for improving work conditions increased following the tragic accident in Dhaka, Bangladesh in 2013 where 1,134 workers died in the Rana Plaza factory collapse (Ashwin, Kabeer, and Schüßler 2020; Fashion Revolution 2021; Niebank 2018). Consequently, consumers have been turning more and more to sustainable fashion items (Lee et al. 2012) and demonstrating a preference to purchase fashion brands with strong sustainability commitments and for substantiating their own ethical consumer identity (Niinimaki et al. 2020). However, very few fashion consumers have voluntarily changed their purchasing behavior to consuming fewer articles of clothing (Vladimirova 2021).

Given the harsh criticism of the fashion industry and the dilemma of fashion being a key element for consumers’ expression of identity, arguably the industry is a cultural domain well fit for the co-creation of greenwashing by businesses and consumers. Applying the concept of co-creation of greenwashing claims to the fashion industry, some consumers evidently want to continue their consumption habits in terms of fashionable items and quantity of purchases. Consumers welcome claims about sustainable products and practices of firms because it provides a way to resolve their own eco-anxieties, but they are reluctant to accept higher prices and less comfortable materials (Joergens 2006; Vladimirova 2021). Accordingly, we can assume that they embrace the sustainability claims of fashion brands and are likely to read them less critically because they benefit from exaggeration of marketing assertions that enable the guilt-free continuation of problematic consumption habits.

**Methods**

To investigate the current recycling technologies for various textile-waste streams, I carried out three case studies to collect data through desk research and interviews with business representatives. Applying a targeted sampling strategy, the cases were selected to cover various recycling methods for textile waste and recruited firms needed to have been in business for at least a decade. The desk research was compiled in graphical templates illustrating the development of the businesses, sustainability impact, and the business model including the components of the standard business-model canvas such as value proposition, value delivery, value generation, and value capture (Bocken, Schuit, and Kraaijenhagen 2018). A special focus was devoted to key technologies and relevant intellectual property rights and collaborations. Given the research interest in addressing the growing textile-waste issue of worn garments, all three businesses were selected on the basis that they were active in the recycling of post-consumer waste (Table 2).

For data triangulation (Yin 2018) and to explore the importance and issues around further recycling technologies in-depth, semi-structured expert interviews were conducted (Black and Fennelly 2021). The experts were identified through conferences, reports, publications, and business events. I contacted eighteen people and ten agreed to participate. Five experts were identified from the fashion and recycling industries, three from research institutes, and two from recycling-industry associations. They were asked to share their personal context-specific knowledge instead of providing official company and business-association statements (Bogner, Littig, and Menz 2009). All case-study participants and expert interviewees were granted anonymity and the option to opt-out. The results are anonymized to rule out the identification of businesses and people (Table 3).

The desk-research phase for the case studies and preparation for developing the interview guidelines started in November 2019. The case-research
interviews and expert interviews were conducted by videoconference or telephone between June 2020 and February 2021. The interviews were recorded, transcribed, and coded using an alternating deductive and inductive approach. The deductive approach used the categories already employed in the interview guidelines such as challenges and opportunities for sustainability specific recycling processes that were based on the literature review. With the inductive process, further categories were developed based on topics and remarks that were brought up by the interviewees.

Results
Following the objective of this article to provide an overview of the status quo and prospects of textile-recycling technologies, the results from the case studies and interviews are presented to correspond with the value chain from collecting to recycling. The coding categories for challenges and opportunities for each step are presented in the following subsections.

Collecting used clothes
The business models differ in terms of which process steps they cover, with some collectors having an integrated sorter. Others are sole collectors that distribute the used clothes further to sorting businesses. Some sorters operate a full or partial mechanical recycling line to process garments. These facilities can include preparation for mechanical recycling, such as removing zippers and buttons and other non-textile attachments. The full mechanical recycling includes cutters to cut garments into small pieces and carding machinery to rip apart and disentangle the fibers out of yarns and fabrics.

To investigate the bottlenecks and opportunities of these different collectors and approaches during the coding of the empirical data two topics crystalized: (1) the revenue streams of professional collectors and sorters and (2) potential increase in environmental impact when fashion-brand companies and retailers collect garments.

Revenue streams of professional collectors and sorters
The standard business model of textile-waste collectors contains major revenue streams from selling secondhand clothes. The majority of European textile waste is sorted in Eastern European and North African countries. The collected garments get separated into reuse, recycling, and trash. A small percentage of reusable garments is diverted to the market for premium secondhand clothes: luxury and popular brands as well as exceptional fashionable designs and more expensive natural fibers such as wool, linen, and silk in good condition. This clothing gets shipped back to secondhand stores in Europe and these premium fashion items form the most important revenue stream for collectors. Sometimes these desirable items are retained in Europe during a pre-sorting step. The rest – the majority of reusable garments ends up in second-hand markets in African, and to a smaller extent Asian, countries (E7, E8). Garments with stains or holes are sorted for mechanical recycling and sold on to recycling companies where they are processed into wiping rags, strips for rug weaving, and fillings and nonwovens for the building and construction industries and the furniture sector. However, sales to mechanical recycling businesses do not generally generate any significant revenues for collectors as the demand is low compared to the availability (C2, C3, E3, E7).

The interviewees, in particular E3, E4, E6, and E7, described how the current challenge is an overall decline in quality, both in terms of fiber materials and brands. Accompanied by the steep increase in donations due to expanded fashion consumption of lower-quality garments, the amount for resale has declined while the amount for mechanical recycling has increased – a currently less profitable field.

Another issue that is challenging the revenue streams is that some countries have raised taxes for
used-clothing imports or issued complete bans. Notable examples are Nigeria, Tanzania, and Rwanda which have acted to protect local garment industries but also to tackle increased littering involving textile waste. This situation arises from the high quantities; items are sold on secondhand markets but also are informally discarded to the environment or used as fuel for cooking (E5, E6, E8). The interviewees expect that more countries may follow.

The third issue that may disrupt the business model is stricter environmental policies to tackle climate change. Textile-waste collectors expect an increase in shipping costs (E6). Since sorting relies on manual labor, to distinguish resalable garments from textile waste for recycling, European collectors usually ship the used clothes to lower-wage North African countries for sorting. Accordingly, increased costs for logistics are expected over the next decade, which increases the pressure to either export less or increase other income from textile-waste collection.

A fourth and final problem that challenges the business model of collectors is an increase in online-resale platforms (E7). These websites allow consumers to sort for sizes and brands. Consequently, collectors receive fewer premium garments because consumers sell them online through third-party vendors. Traditional secondhand markets were not generally viewed as under threat as it is not worthwhile for end-use consumers to sell single clothing items and the sale is not targeted at popular brands. The online platforms now compete for premium secondhand clothes.

**Take-back systems of fashion brands**

Next to the professional collectors and charities, an increasing number of fashion brands have installed take-back systems similar to sellers of consumer electronics, cars, and white goods. This is in line with the waste directive and producer-responsibility directives of many countries that require producers to recover their products at the end of their life and to then organize waste treatment in the most sustainable way. Four different approaches can be distinguished, with fashion businesses using either one of them or a combination: (1) free mail returns to take back used garments, (2) collection of used garments in stores, and (3) donation incentives by providing vouchers for new purchases. Usually, businesses implement these three options in ways that allow consumers to hand back any brand. More upmarket outdoor-clothing brands and ecological brands take a fourth approach that involves (4) purchasing used garments of their own brand and selling them on their online-market platform.

E1 and E2 explained that fashion brands communicate their take-back incentives as part of CSR activities and sustainability reporting as well as a form of advertising to consumers. These programs are also promoted on company websites. Some department stores advertise purchasing vouchers for used clothing donations at special shopping events. C3 highlighted the importance for fashion brands to market sustainability stories. Consumers do not just buy an appealing garment, they purchase a lifestyle promise. Because social media and the Internet have become major marketing platforms, fashion brands are always in search for good sustainability stories to gain the attention of bloggers, influencers, and customers.

According to E1 and E4, the fashion brands and retailers do not implement their own sorting and recycling facilities. They work with large, established sorting and recycling businesses. Only very few and mostly small ecological brands that take back their own products repair and recycle them into new products (C2).

**The sorting process: increasing demand and automation technologies**

Sorting is a manual process where workers have about 2–3 seconds to decide on the quality of a garment (C2). For some recycling businesses, the clothing gets sorted according to fiber materials; for instance, for some specific applications only cellulosic fibers or synthetic fibers are required. Processing textile waste through mechanical recycling into nonwovens for mattings, packing material, and insulation can be done with multi-fiber compositions (E5, E9). Sometimes a pre-sorting step into garments for resale, recycling, and trash is followed by a more detailed sorting into different types of materials for mechanical recycling. As mentioned already, sorting is a labor-intensive manual process and consequently takes place in low-wage countries. It is important for recycling companies to build long-term relationships to guarantee high labor standards. With the expected increase in textile-waste streams due to the EU waste directive that requires member states to collect used textiles as a separate waste stream by 2025, C2 points out that this will lead to enlargement of the number of sorting companies as the increase is too drastic for existing businesses to handle it by expanding operations.

Distinguishing among different human-made cellulosic fibers or between different synthetics is often not possible for sorters. Current chemical-recycling processes require homogenous fibers to be efficient, such as pure polyester or polyester-cotton blends.
Hence, industrial waste is preferred for chemical recycling because collecting standardized textiles is easier (E5). Automation technologies for fiber sorting with near-infrared spectroscopy (NIRS) is already used in the recycling of plastic packaging. Current research projects are further developing it to be suitable for fiber sorting (E9, E10). However, this technology is not expected to replace pre-sorting in the near-term future.

Radio-frequency identification (RFID) tags are sometimes discussed as a promising technology for tracking fiber compositions as labels get cut out or fade (C6, C9). They are used by professional workwear-service companies that rent and launder the garments for large firms. This is also the area where the majority of chemical recycling of polyester is done, e.g., by Teijin. In the fashion industry, some premium brands use RFID tags to distinguish original products from counterfeits. For ordinary fashion items, the interviewees argued that it would only increase the electronic waste issue as consumers may cut it out and it is a development that will not result in an increase in recycling volumes. Instead, according to E4 and E7, more recycling businesses should first be set up.

The recycling process

All of the actual recycling processes hold potential for further improvements, according to the case studies, each of which registered growth of their recycling activities, and to the interviewees. An open issue is how to inform consumers in order to leverage their sustainability choices and to increase demand for recycled products.

Transparency of recycling to consumers

According to C3, textile recycling has only recently gained momentum as a positive trend in public awareness. Mechanical recycling technologies that were developed due to resource shortages a century ago have been around for the last several decades but stayed under the radar of consumers. New materials for products were more appealing. If insulation fillings – for example for winter coats – were a blend of new and recycled materials this message was not effectively communicated, in part because current modes of textile labeling do not distinguish between virgin fibers and recycled fibers. Fashion brands may choose to add a “r” in front of the abbreviation of fibers to indicate that they originate from recycling. But also innovation in mechanical recycling of post-consumer textile waste slowed down with new fibers becoming cheaper (C2).

According to C1, the cradle-to-cradle (C2C) certificate issued by the Cradle to Cradle Products Innovation Institute is gaining importance in the fashion and textile industry. Some fashion brands have received certification for cotton products such as t-shirts and denim trousers. The certificate distinguishes between five different levels with the aim of incentivizing producers to reach the next level. A high score at the gold level, however, does not say anything about end-of-life treatment and it does not indicate if the product gets recycled or how cost effective and commercially attractive it is to recycle the item. Other than the C2C label, there are no significant labels on the market to guide consumers. The majority of certificates are for good environmental practices, fair labor standards, or toxic-free products in general (E2).

Comparison of recycling solutions

For mechanical recycling, the garments are cut into pieces then the small cloth fragments are torn apart until single fibers are entangled and carded into new rovings – the mat of fibers that serves as pre-yarn. Because the fiber length deteriorates during mechanical preparation, usually virgin fibers are included to actually spin out new yarns, which are used again for weaving and knitting of the fabrics for new garments (C2, E2, E7, E8). An advantage of mechanical recycling is that the process is much less susceptible to interferences due to multi-fiber compositions. Improvements are still possible with current spinning machines to process mechanically recycled fibers (C2).

According to some of the interviewees, chemical recycling is more promising for large-scale closed-loop recycling to tackle textile waste (E4, E7, E10). Others see mechanical recycling as having larger potential (C2, E3). Biological recycling appears to be interesting for cellulosic fibers, but is not seen as an important building block for a sustainability transition in the next decade (E9). The interviewees agreed that both recycling methods will coexist and require further improvements to process post-consumer waste more efficiently.

In general, current recycling methods result in more expensive yarns and fabrics (E1, E6). As the garment industry has developed over the years into optimizing mass production, recycled yarns and fabrics need to be available on a larger scale and in a more homogenous quality (E7). Thermal-mechanical recycled polyester from PET bottles is already used, as there is a steady supply available (E1, E2). According to C3, fashion-brand companies have to provide customers with sustainability stories. They embrace initiatives involving fibers made of plastic collected from the oceans and beaches, but the supply of this waste for new garments is limited. Accordingly, rPET from bottles is seen as the next
best alternative as new fibers from textile waste are not available yet in large enough quantities at reasonable prices (E2).

Discussion

The results point toward three discussion points concerning the collectors and sorters and increasing recycling in general. The aspects are elaborated in the following section and summarized in Table 4.

Challenges to revenue streams of professional collectors and sorters

The results confirm an increase in garment donations accompanied by a decrease in the quality of discarded clothing (Brydges, Retamal, and Hanlon 2020). This situation is challenging the business model of established collectors and sorters. Financing the collecting and sorting of used clothes by selling premium secondhand items cannot be sustained as an expansion in premium apparel relative to donations is unlikely and secondhand platforms for consumers will continue to grow. At the same time, the results reinforce the argument that selling worn garments to Asian and African secondhand markets is being challenged by contentions that garment imports hamper local garment-production industries (Manshoven et al. 2019). It has been difficult to investigate this claim because of the methodological complications of distinguishing whether the decline of domestic clothing manufacturing is due, on one hand, to general globalization trends, lack of infrastructure, inefficient businesses, and cheaper imports or, on the other hand, to used-clothing imports (Brooks and Simon 2012). However, the number of countries that adopt a critical view on used-clothing imports is rising, as the claim seems plausible and textile waste is also littering the environment in developing countries. Even the government of India, one of the top importers of worn clothes, was urged in 2019 by the National Committee on Textiles and Clothing to stop the imports which are mainly from China, Bangladesh, and Indonesia (The Hindu Business Line 2019). Other challenges exposed by this study include increased use of consumer-sales platforms and an expected increase in shipping costs.

Accordingly, collectors are facing a situation where they need to change their revenue streams. Consistent with policy suggestions to provide financial incentives and obligations such as quotas for reuse and recycling (e.g., van Bahr et al. 2019), a solution may be the true-cost approach (Picciu 2014) which asserts that a percentage of the cost of end-of-life treatment of garments should be incorporated into the sales price. Some eco-label companies are practicing this already (Manshoven et al. 2019).

Table 4. Challenges and opportunities to increase post-consumer waste recycling.

| Building block and organization in value chain | Challenges | Opportunities and possible solutions |
|-----------------------------------------------|------------|------------------------------------|
| Collecting -Professional collectors           | Revenue streams require change due to fewer premium secondhand donations and increasing waste Increasing import taxes and bans on secondhand garments Expected increase in shipping prices due to increasingly stricter environmental regulations for logistics | True-cost approach to incorporate environmental impact issues in virgin-fiber price Responsibility of fashion businesses for whole value chain including end-of-life solutions could incorporate garment-price increase that goes to recycling businesses, e.g., per item per weight and recyclability |
| Collecting -Fashion businesses               | Vouchers and stationary collection systems may provide purchase incentive for increased consumption Mailing options increase carbon footprint compared to stationary collection systems | Take-back systems should not provide purchase incentives such as vouchers but instead improve consumer education about recycling |
| Sorting                                      | Increase in waste accompanied by increase in sorting businesses may lower labor standards Automatic sorting technologies do not solve pre-sorting for secondhand markets | Extended producer responsibility could include labor standards at sorting Pre-sorting by consumers: differentiating between good condition and worn such as differentiating between glass colors in Germany Further development of automatic sorting RFID and QR codes helpful for professional workwear-rental businesses |
| Recycling                                     | Virgin fibers are too inexpensive rPET from PET bottles diverts resources from packaging industry instead of incentivizing recycling of worn clothes | True-cost approach to incorporate environmental impact issues in virgin-fiber price Responsibility of fashion businesses for whole value chain including end-of-life solutions Commitments to recycling of fashion businesses should include worn garments in order to rethink their designs for recyclability Transparency also in terms of labels whether circularity labels include take back and recycling |
Higher retail prices are unlikely to be a popular strategy, both for consumers and fashion-brand companies and it is doubtful that it will happen on a larger scale without policy intervention.

Consumers certainly need to be educated that sustainability of the fashion industry requires higher prices and that they can reduce the impact of garments if they purchase clothes made of recycled fibers. This could be incorporated already in school curricula as natural science and applied mathematics projects, as garments are objects that everyone wears. Revising textile labeling to clearly indicate recycled fiber materials and recycling labels may help only very few consumers to guide their purchase decisions, as they hardly consult labels.

**Leverage in collecting garments: charities and fashion businesses**

As textile waste is increasing, the number of sorting businesses in low-income countries grows as well. When the EU directive goes into effect in 2025 to collect used clothes as a separate waste stream, established collectors and sorters may have difficulties keeping up. Rapid growth in sorting demand poses a threat to labor standards that is similar to other waste-sorting industries such as consumer electronics (Bauck 2020). According to the results from this study, automation in sorting is unlikely to solve this issue, as pre-sorting in resale, recycling, and trash will continue to be performed by manual labor for the foreseeable future. Consequently, clear policy measures are necessary to limit the social costs associated with growing textile waste. On a policy level, extended producer responsibility and waste directives should encompass requirements for labor standards in the sorting sector.

Charity organizations that license their names to collectors could require that the authorization includes obligations to provide responsible labor standards throughout the recycling value chain and, in particular, for the sorters. It is questionable whether consumers are aware that charity organizations simply license their names. I argue that they have a moral obligation with respect to consumers to leverage their power if they provide their names for garment donations. I assume that this may contribute to drive recycling without increasing social costs.

**Is rPET from plastic bottles and take-back systems with purchase incentives sustainable action or greenwashing?**

Fashion-brand companies and retailers as collectors could have a positive impact but their activities could also backfire on the environment. According to the results of this study, there are three issues associated with the collection of used clothing by brands. First, customers might assume that fashion-brand companies and retailers know the fiber composition of their products and recycle them more efficiently. Such circumstances could lead to presumptions that these businesses have better performance in terms of sustainability and CSR than they actually do. The second issue is when fashion brands and retailers provide purchase incentives for new clothes in exchange for used clothes. Implementation of this strategy very likely increases fashion consumption. A third open question is the sustainability impact of returning used clothes by mail. The environmental impact of small parcels as compared to stationary collection boxes is estimated to be higher (Escursell, Llorach-Massana, and Roncero 2021). As long as fashion-brand companies and retailers simply transfer the used clothing to collectors and sorters, it adds little value. On the contrary, I argue that it is more of a marketing strategy to improve customer relations and to add to sustainability activities in CSR and sustainability reporting. Accordingly, even though it is a legal responsibility of fashion retailers in many countries to take back products at the end of their life (EC 2018), advertising it as sustainable action has a flavor of exaggeration and could be deemed greenwashing as defined by its subtler expression (de Jong, Huluba, and Beldad 2020). Instead, fashion-brand companies and retailers could also use their power – equivalent to charity organizations – to assure that sorting and recycling is done in accordance with responsible labor practices and environmental standards.

While all recycling methods have further potential to grow, the results indicate that new fibers and garment manufacturing is still too inexpensive for recycled fibers to be competitive. Recycling polyester bottles into fibers diverts resources from the packaging industry and de-incentivizes recycling technology advancements for used clothing. Accordingly, the strong focus of fashion-brand companies on rPET from plastic bottles as a raw material for sustainable products – the cheapest recycled fiber with the lowest environmental benefit from all recycling approaches – overcomes consumers’ reluctance to change fashion-purchasing habits that are rationalized on the basis of a greenwashing co-creation process. Instead of using rPET from plastic bottles, fashion businesses would improve their environmental impact by focusing on design for circularity, as already suggested for instance by Ho and Choi (2012).
Conclusion
The results of this study reveal that various initiatives are promising, such as chemical recycling of cotton and polyester, and take-back systems by denim brands that convert used garments into new fabrics. However, industry structures and business models need to be re-orientated to boost these recycling concepts as to date they have failed to continuously finance collection and sorting systems. The current investigation revealed that collectors will not cope with an increase in worn garments if they do not change their revenue model. At least in the EU, this situation encourages policy action to support smooth implementation of the new requirements to collect textile waste as a separate waste stream. The results can also be read as a need to further improve the current waste directive of the EU (2018), to really compel producers and sellers to take responsibility for recycling, and to incorporate the associated costs into the retail price of garments. In particular, fashion-brand companies and retailers, as well as charity organizations, should use their market leverage to enforce high environmental and labor standards in sorting and recycling and waste policies could require the industry to provide collection and recycling options that do not incentivize an increase in consumption. Here, further research is necessary to explore suitable collection options that may even entail pre-sorting by consumers.

Also, further technological advancements are required for all recycling processes to become competitive for new fibers. While chemical and biological recycling are being promoted as ways to produce high-quality fibers, the findings indicate that mechanical recycling holds potential as well for further improvements and has the advantage that it is less susceptible to impurities and is already broadly established. This trend can be accelerated if the cost for virgin fibers increases. As market-pull mechanisms, educated customers are important to increase demand. They could potentially be reached by labeling that acknowledges actual recycling instead of recyclability.

To drive recycling as part of sustainability transitions, along with further innovation of recycling methods, research needs to focus on how to build adequate industry structures. This should not be limited to the collectors, sorters, and recycling businesses. The roles of consumers, fashion-brand companies, and retailers need to be considered as parts of this value network. Incentives for fashion businesses to design for recycling and to actively take responsibility for the end of life of their products merits further investigation. It is also important to note that recycling may slow down more fundamental changes toward sustainability in the fashion industry. As an end-of-life solution, it may contribute to the perpetuation of trends of increasing material consumption. An in-depth analysis of the sustainability benefits of recycling also provides an important avenue for further research of high societal relevance.

Acknowledgements
Special thanks to Andreas Tauber for helping with the literature review and editing, and to the reviewers for carefully reading and providing helpful suggestions to improve the article.

Disclosure statement
No potential conflict of interest was reported by the author.

Funding
Some of the interviews were conducted within the project IPACST which is financially supported by the Belmont Forum and the NORFACE Joint Research Programme on Transformations to Sustainability which is co-funded by the German Aerospace Center/Federal Ministry of Education and Research (DLR/BMBF) Research for Sustainability (FONA-SÖF) [01UV1812A] and [01UV1812B], Global Challenges Research Fund, Economic and Social Research Council [ES/S008322/1], Swedish Science Council (VR) [2017-06439], and the European Commission through Horizon 2020.

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