Chapter

Design for Recycling of E-Textiles: Current Issues of Recycling of Products Combining Electronics and Textiles and Implications for a Circular Design Approach

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Abstract

Circular economy principles and eco-design guidelines such as design for recycling gain increasing importance to improve recyclability of products. The market of textiles with electronic components—so-called electronic textiles (e-textiles)–grows quickly entailing an increase in waste due to obsolete and defect products. This chapter presents insights into the current state of e-textile recycling in Europe. As electronic recycling differs from textile recycling, a survey of sorting and recycling businesses in Europe was conducted to obtain insights into the current and future handling of e-textiles. The survey results reveal that e-textiles have so far played a minor role for sorting and recycling companies, but about one-third of the businesses already experienced issues in recycling e-textiles. While some of the respondents have already developed processing concepts, the overall occurrence of e-textiles is so low that businesses are unlikely to develop recycling solutions. However, with increasing market volume, waste will also increase and recycling requires improvement to reduce environmental impact. Based on the survey results, recommendations for improving the recyclability and recycling rate of e-textiles are proposed. This includes expanding the scope of current regulations to e-textiles to apply guidelines for integrating sustainable end-of-life solutions in the product design process, acknowledging current shortcomings of the recycling industry.

Keywords: circular design for e-textiles, eco-design, electronics recycling, e-textiles, textile recycling

1. Introduction

E-textiles experience an increasing popularity in both consumer product markets as well as the research community. The global market volume of e-textiles is expected to more than double from 2021 by 2026 [1]. Over the last decades, research and development of e-textiles focused on increasing the wearing comfort, robustness, reliability, and cleaning ability of the products as these properties are crucial for user acceptance [2]. One way to improve these properties is to miniaturize the electrical circuitry and fuse it to or combine it with the textile substrate [3]. However, this trend toward a high degree of integration of the electrical components into textiles leads to challenges in terms of reparability and recycling of e-textiles and their components [4]. Recycling of textile products due to different fiber material combinations, auxiliaries, such as buttons and zippers, and various chemical treatments is already difficult and hardly practiced. Also recycling of electronics because of different, strongly connected materials is challenging. Due to their hybrid nature, recycling and recovery of reusable resources from e-textiles are even more challenging than for pure textile or electronic products. Particularly, because waste collection and recycling businesses are either specialized on textiles or on electronic products.

Hence, this chapter aims to shed light onto the current processing of e-textiles in sorting and recycling companies within Europe. It provides insights into product features and conditions that must be met to ensure the recycling of e-textiles. Furthermore, it provides recommendations on conditions that have to be fulfilled to develop circular product life cycles of e-textiles. The insights into the current state of recycling and waste management for e-textiles within Europe, including challenges and possible solutions, are based on a survey among sorting and recycling companies in the textile and electronics sector conducted in the year 2021.

Circular economy principles include reuse, repair, and recycling [5]. In order to improve the reuse, reparability, and recycling of e-textiles, circular design principles should already be incorporated in the design stage. But how can we achieve this effectively for e-textiles? Based on the results of the survey, we propose that it needs to be governed top-down. A bottom-up approach from the industry is not likely to happen due to the small quantities of e-textiles.

The European Union (EU) committed its member states to sustainability transitions of manufacturing industries, among other strategies by moving toward a circular economy [6]. Other regions and states, such as China, India, Japan, and the United States of America, strengthen their commitments to circular economy and sustainable manufacturing [7–9]. Consequently, the results of this study are relevant to other territories, which are committed to sustainability transitions of manufacturing industries. As the United Nations Sustainable Development Goals (UNSDG) gain importance around the world for transforming economic activities to sustainability, the results of this study presented in this chapter contribute to UNSDG 9—Industry, Innovation and Infrastructure, and UNSDG 12—responsible consumption and production.

The chapter is structured as follows: Section 2 provides a short introduction into e-textiles and their current market development. Section 3 explicates the survey method and data that was conducted to obtain insights into the current and future handling of e-textiles by sorting and recycling companies. Section 4 presents the results of the survey, including a discussion. Section 5 summarizes the main conclusions and proposed ways to improve recyclability of e-textiles.

2. Current trends and challenges in product design, markets, and recycling of E-textiles

E-textiles are combinations of electronics and textiles. They consist of electronic components such as circuits, sensors, and lights for achieving functionalities of garments and textile products. Application examples include conductive components for sensing and actuating, communicating, and microprocessing information such as acoustic and motion signals [10]. The products range from monitoring health status of patients, tracking body functions, speed and routes for personal feedback in professional sports products, at leisure sport and fitness exercises, safety performance such as light signals, to acoustic combinations connectable to mobile devices for leisure [1, 3, 10–11]. Against the backdrop of the growing market of e-textiles with a global turnover expectation of about US$ 1.3 billion by 2032 [12], the e-textile waste will increase accordingly.

Current research reveals that the shortcomings of durable integration of electronics and a lack of standards to analyze the performance are still major reasons for market failure [13, 14]. Test standards are still under development [1]. A current trend to improve longevity of e-textiles is through miniaturizing electrical circuitry and combining it with the textile substrate. The electronic components need to be fixed onto or inside the textile structures, which is done through different processes such as gluing, welding, brazing, and soldering. These joints between rigid electronic components and flexible textile substrates are often the critical product feature that is most likely to fail. A current development trend is to integrate conductive threads through knitting, stitching, sewing, and weaving into fabrics as well as printing circuits onto textile structures, instead of usage of conventional electronic components such as cables and circuit boards mounted on hard plastics [15, 16]. These electric conductive textile substrates, also known as fiber-based devices, appear to be promising to enable comfortable and durable solutions [17], and improving the washability of e-textiles [18]. However, a high degree of integration of the electrical components leads to challenges in terms of reparability and recycling of e-textiles.

Electronic waste and textile waste have different collection and recycling systems that differ among European countries. In Germany, for example, waste collection falls under communal services, and municipalities work with a variety of private businesses and charity organizations to enable collecting, sorting, recycling, and resale. While consumers bring back defect electronic and electrical products to where they have purchased them, lately, also fashion brands take on more responsibility in actively communicating to consumers that they can dispose their used items at the producers and offer take-back systems [19]. Overall, the textile and electronic waste collection in the EU is still under development, with electronic waste collection being more advanced than textile waste collection and high percentages being disposed in household trash and end up in landfills.

Electronic recycling and textile recycling both face several issues. Both require careful sorting to guarantee efficient and high-quality recycling, and for both product groups, the recycling rate is rather low, given the complex product compositions. As for textile recycling, different fiber compositions and auxiliaries make automation in sorting and processing rather challenging. The mandatory product labels that indicate the raw material compositions are often cut out by consumers, wear out through washing, or are wrongly labeled right from the start [20]. While the overall recycling rate is rather low including packaging and other waste, the EU sets targets to increase recycling and recovery of resources. For textiles, the low cost supply of new raw materials is a serious barrier to improve and increase recycling [19]. The current business model of textile sorting and recycling businesses is based on resales of high-quality second-hand garments. With decreasing quality of used textiles and a steep increase in second-hand markets that are organized through internet platforms and enable users to directly sell their apparel, the waste recycling businesses require new sources of income to sustain [19, 21].

The EU has strict regulations on the treatment of waste in general, which is continuously adjusted and guides the waste treatment in the member countries. With the aim to transition to sustainable manufacturing and consumption, further initiatives on EU and on national level guide the treatment of textile and electronic waste that facilitate recycling. However, not all countries have implemented the stricter recycling and recovery regulations [22]. The treatment of electronic components falls under the EU directive on waste electrical and electronic equipment (WEEE Directive) [23]. Along with stricter electronic and textile waste regulation, especially for disposal of WEEE criminal activities increased, resulting in illegal landfills, which primarily occurred in low-income countries [24]. This development reveals the issues at stake, that with increasing costs for waste treatment, the institutions to enforce proper waste treatments need to be strengthened as well to counteract false disposal. Hence, concepts and technologies for waste treatment should be advanced and implemented on a global scale to be effective [25].

3. E-textile recycling in Europe: survey method and data

The two main components of an e-textile are the textile substrate and the electronic and electrically conductive components. Based on this, two target groups were defined for the survey: (1) electronics collectors and recycling businesses, and (2) textile collectors and recycling businesses. Applying a purposive sampling strategy, using industry websites, 506 businesses from electronics recycling, 179 from textile recycling, and 81 with cross-sector expertise were identified and requested to participate per email, in English and in German language. The processing time of the survey was approximately 15 min, which was conducted online using the survey tool "LimeSurvey."

In total, the survey consisted of 46 questions for electronics and 47 questions for textiles. According to the prior experience with e-textiles, not all questions required a response with about 10 questions being optional. The questions addressed the extent to which e-textiles are recognized in sorting and recycling companies within Europe and already processed in a suitable way. The survey included a list of product features and conditions that may facilitate the recycling of e-textiles. The features and conditions were identified based on an extensive literature research and discussions with recycling experts. The option to add further characteristics and conditions enabled respondents to expand the predefined list.

To increase the response rate, the survey was carried out anonymously. The survey has a coverage bias as it was conducted online, which requires a stable internet connection, and the companies needed to have an email address, which excludes smaller sorting and recycling businesses in rural regions. A response bias may also occur due to a desired external presentation of the company or in the course of internal confidentiality or security agreements, despite the fact that the survey has been anonymized. Politeness or the desire to complete the survey despite a lack of expertise can also contribute to a bias in the results [26]. The non-response bias includes decisions not to participate or stop participation. Direct declines gave usually the lack of time due to the persistence of the Covid-19 pandemic as their reason. It is conceivable that smaller businesses in particular did not participate in the survey due to a lack of time and personnel.

The data were collected during four weeks in June 2021. The response rate of complete datasets was 6.13%. With regard to sector classification, a bit more than half of the respondents (57%) belong to the sorting and recycling sector in the field of used textiles, the others operate sorting and recycling of e-waste. Within the EU, most processing facilities of the companies that participated in the survey are located in Germany, followed by Lithuania, Poland, Spain, and Hungary. About 6.7% of the companies operate sorting and recycling facilities outside the EU, such as in Macedonia, Switzerland, and the United Arab Emirates. Outsourcing outside of the EU occurs only for textiles and not for electronics. In terms of how well the respondents represent the recycling industry in the EU, it is important to note that a large cluster of textile sorting and recycling businesses exists in East European countries [27]. However, the purchasing ability in Western European countries is higher; accordingly, a higher amount of e-textile waste can be assumed in the dominant region of the respondents. Also, the textile waste collection and recycling facilities are very structured in Germany, as compared with other countries [28]. Hence, with the majority of respondents from Germany, the results could be interpreted in terms of perspectives from advanced sorting and recycling regions.

The respondents that operate in electronic waste claimed to sort WEEE into defined categories (37%), disassemble them into their components (22%), and process WEEE as second-hand goods or recycle it mechanically (19%). Only one business claimed to recover precious metals. However, all of the respondents forward the waste at least partially to external companies for recycling and recovery processes and for reuse as second-hand goods. None of the respondents forward the WEEE outside of the EU. This might be due to stricter regulations of the electronic waste trade as compared with used textiles.

Regarding used textiles, 32% of the respondents stated that they sort into defined categories, and about 26% reprocess the used textiles as second-hand goods. Mechanically recycling of textiles is done by 23%, and only 13% of the companies indicated that they use thermal recycling for energy recovery. However, as thermal and mechanical recycling is the most common approach, this may be outsourced to others, so that the respondents do not do it themselves. In fact, about 75% of the businesses that sort used textiles exclusively have outsourced processing operations to others, such as recycling, recovery, or reprocessing into second-hand goods.

4. Current state of E-textile recycling: survey results and discussion

The study is guided by the question, whether e-textiles are recognized in sorting and recycling companies within the EU, and processed in a suitable way that addresses both the electronic and the textile components. Accordingly, the study contained a question about the occurrence of e-textiles in the recycling process. The sorting and recycling companies responded that currently the quantities of e-textile waste that show up at their businesses are rather low to very low. The e-textiles originate from textile container collections (33%), from hospitals and industrial manufacturing (17%), and from municipality WEEE collection points (17%). The rest steams from unknown sources. The e-textiles had integrated, flexible printed circuit boards, and stretchable printed circuit boards, embroidered circuits, as well as integrated textile circuit boards. Whereas printed and stretchable circuit boards showed up at both subsectors (electronic recycling and textile recycling), the e-textiles with embroidered circuits and with integrated textile circuit boards only showed up in textile sorting and recycling businesses. They did not get processed except for thermal recovery, whereas the others with printed circuit boards got either forwarded to second-hand markets or separated into textile and electronic components and got processed further accordingly within electronic and within textile recycling.

Regarding existing processing concepts for e-textiles, 28.6% of the textile and electronic sorting and recycling companies stated that they already process e-textiles.

In total, 37.5% stated that they do have a processing concept. The businesses with processing concepts usually sort the waste based on the type of e-textile, high quality gets forwarded to second-hand markets and for lower quality, the components get separated. In a next step, the textile content gets mechanically separated and processed into fibers for nonwovens, for example, for cleaning rags or insulation material, or for new fabrics. Energy recovery is also quite common. The electronic sorting and recycling businesses claimed that they would recover secondary raw materials such as precious metals from the electronic parts. It is conceivable that e-textiles that have occurred in the companies to date have not been documented with details of their construction type. This makes it difficult to draw conclusions about the occurrence of different e-textile systems and their current recycling.

The respondents were not aware of any business that specialized on recycling of e-textiles. This appears plausible given the very few products that end up at recycling facilities. While 62.5% of the companies in the textile sector can reliably identify e-textiles during processing operations, 37.5% of all companies stated that they experienced difficulties during further processing of e-textiles in the past. This was among other issues due to e-textiles that remained undetected. The undetected e-textiles caused reduction of the quality in terms of purity grade of the recycling streams. Accidental shredding of these components contaminates the recycling streams. One respondent explained that there may be an additional fire hazard. The respondents confirmed that a high integration of electronics and textiles is difficult in recycling. Especially permanent bonds between the textile substrate and conductive yarns such as for e-textiles with embroidered circuits cannot be disassembled so far. Consequently, they get sorted out for thermal recovery.

The future emergence of e-textiles is estimated to be rather low and very low by the majority of the respondents (82.3%). Although a strong market increase of e-textiles is forecasted for the next decade [1], it will continue to make up only a small segment of the overall textile and electronics markets in the future. Thus, the market volumes of regular textile products and electronics will continue to exceed the market volume of e-textiles by a multiple. Given the low volume of market-ready e-textiles, there does not seem to be any urgency for recyclers to develop specialized processing methods at this stage. It is likely that processing methods specifically designed for e-textiles are not yet economically viable or cost-covering for the companies. This may result in lack of action, with the industry failing to develop efficient solutions for e-textiles. Accordingly, it should be governed top-down by policymakers, as the quantities are too low for industry to develop bottom-up solutions.

To recycle e-textiles efficiently, the companies explicated various requirements and conditions. These requirements include product design that allow easy disassembly, reliable identification of electronic components, clear waste regulations to help consumers understand how to dispose e-textile waste properly, the development of integrated factories that can process both textiles and electronic components, the documentation and evaluation of processes for reliable data, and a general improvement of the recycling processes of electronic waste and textile waste. Electronic and textile waste both operate on a very low margin, and the processes to regain high-quality resources for further products are still expensive.

In order to identify e-textiles in sorting, the product labeling regulations could include specific markers. In case of non-detection, sorting companies exporting end-of-life textiles to third countries run the risk of exporting e-textiles together with other textile waste. This may constitute an illegal export of e-waste to third countries. In the survey, we asked about feasible ways to mark e-textiles from a sorting and recycling perspective. The respondents had different views on the practicality of various markings to facilitate reliable identification of e-textiles. About 11% stated that standardized markings were not necessary for the identification of e-textiles and that a visual inspection was sufficient. About 22% found a text on the sewn-in tag in the product practicable, and about 22% considered RFID tags useful. In total, 19% voted for printed or embroidered text on the textile surface, whereas 15% found an embroidered or printed QR code on the textile surface the best solution, and 11% selected QR codes onto the sewn-in tag or color stripes. The use of chemical marker was also mentioned as an alternative solution for efficient and reliable identification of e-textiles. This can enable time-efficient detection of e-textiles in the near-infrared range, which would eliminate the need to search for a marker. Overall, the variety of answers reflect the uncertainty and need for a practicable solution to mark e-textiles.

Product marking with RFID tags adds an additional microchip and antenna-based electrical component that must be properly processed at the end of the product's life. To find out whether the textile sorting and recycling businesses have already experienced difficulties with RFID-tagged products, the companies were surveyed in this regard. About 28% reported that difficulties already occurred due to integrated RFID tags during processing operations. Specifically, difficulties arose in sorting products correctly according to their RFID tags. In addition, one business indicated that problems were suspected to occur during mechanical and chemical recycling processes. One business from the electronic sorting and recycling sector stated that there was no RFID detection in primary treatment plants and that the sensor technology in sorting plants can react to RFID tags with error messages.

The majority of respondents (about 81%) agree that special collection systems for discarded e-textiles would support proper recycling. However, the remaining 19% disagree with the statement. The issue that users dispose their waste incorrectly despite collection systems and awareness campaigns could be the reason why the respondents have rather different views on the value of specially dedicated collection system for e-textiles. The other reason may be the low quantity of e-textiles, which hardly justifies dedicated collection systems. Hence, take-back solutions by producers or disposal at WEEE collection points at municipalities are likely to be sufficient.

Waste regulations need to be combined with campaigns to inform users of e-textiles. To efficiently process end-of-life e-textiles, end users need sufficient knowledge about the proper disposal. As the quantity of e-textile waste is still very low, we asked in the study about the sufficiency of knowledge on proper disposal of textiles and electronics. The different responses from textile sorting and recycling businesses as compared with electronic sorting and recycling show that knowledge of proper textile waste disposal is lower. Regarding used textiles, only 12.5% of the respondents that operate in textile waste rated the knowledge of end users for the proper disposal as rather sufficient. About 68.75% stated that the existing knowledge of end users is rather insufficient, and the remaining 18.75% claimed that end users lack appropriate knowledge. The knowledge how to correctly dispose WEEE appears slightly better with 50% of the electronic waste treatment businesses considered the knowledge of end users to be rather sufficient. Only 33% find the knowledge rather insufficient, and again the remaining 17% rate it as insufficient. The knowledge that wrong disposals of electronic and electrical components pollute the environment and that the contained metals should be recovered is probably more widespread than the consequences of disposing used textiles in household trash. With textiles, the awareness campaigns may be also challenged by the perspective that used garment exports may destroy apparel manufacturing industries in developing countries; hence, various states implement import stops or high import taxes for used textiles [29].

The awareness campaigns could also involve users in such a way that they separate the electronic or electrically conductive components and the textile substrate and accordingly dispose the different parts into the textile and the electronic waste stream. However, this requires a modular design that enables the separation of the components. The application of the eco-design strategy "design-for-recycling" in the product development process was rated by all except one respondent as an opportunity to improve the recyclability of e-textiles. Furthermore, about 88% agreed that the extension of the scope of the WEEE Directive may lead to an increase in applying design-for-recycling during product development of e-textiles. By extending the scope, e-textiles can be classified under the categories of "Small equipment" and "Small IT and telecommunication equipment" depending on their intended use. Consequently, applying a holistic product planning can facilitate the development of concepts for separate end-of-life processing. Encouragement of research, documentation and evaluation, and the development of best practices may provide access to reliable information and databases in the future. Again, this must be governed by stakeholders from the policy domain, as the recycling sector is unlikely to initiate it. Given the low quantities of e-textiles, there is no apparent reason for the recycling industry to develop solutions.

To drive holistic and efficient recycling of e-textiles, collaboration and sharing of information and best practices among companies in the textile and electronics recycling sectors are essential. Nonetheless, about 88% of the respondents indicated that no cross-sector collaborations existed to date. This may be attributed to the low volume of e-textiles. Hence, industry associations can play a role to facilitate the joint development of processing concepts and assess and suggest suitable processing equipment for e-textiles.

It should be noted that modular product design with the aim of better recyclability is currently still a topic that tends to receive little attention in the field of research and development of e-textile systems. This is also reflected in the low availability of publications on this topic. Modular product design in the field of e-textiles is currently mainly utilized in the context of building kits for rapid and accessible prototype development [30–33]. Fiber-, carbon-nanotube-, and graphene-based electronic and electrically conductive components primarily aim at improving the reliability, comfort, and functionality aspects of e-textiles [17, 34, 35]. Highly integrated electronic and electrically conductive components are difficult to separate from the textile substrate, posing a challenge for sustainable product development. Reparability and maintenance by end users becomes difficult or impossible. Likewise, it is questionable whether product-responsible companies with internal or external repair services can repair highly integrated e-textile components without damaging the textile substrate. Simply replacing defective products should not be considered a sustainable solution, as it would create further waste and resource consumption. Insufficient reparability promotes short product life cycles through premature obsolescence. Nevertheless, it is conceivable that a modular or semi-modular product design would meet with approval from end users and other stakeholders.

5. Conclusion and outlook to improve e-textile recycling

The results of the study reveal that e-textiles have so far played a minor role for sorting and recycling companies in Europe: e-textiles are not commonly found products at sorting and recycling companies. Consequently, only about one-third of the businesses already have specialized processing concepts for e-textiles. During sorting, e-textiles are recognized to some extent; however, the technology and machinery of sorting and recycling companies are not designed for the processing of e-textiles. The low waste quantities also lead to a lack of urgency to develop special recycling concepts for e-textiles. Even with a higher market volume, they still will make up a very small percentage of textile and electronic waste streams.

The results of the survey also provide insights into the conditions that must be met to ensure the recycling of e-textiles. Sustainable product development that applies eco-design strategies such as circular design approaches acknowledging end-of life treatment can improve the recyclability of products. It can also help to comply with current and future EU directives and legislation. Especially a modular product design may simplify the separation of e-textiles. This would enable the use of existing processing infrastructures for used textiles and e-waste through collaborations across electronic and textile recycling companies. As currently ease of separation implies also a compromise on longevity of products, e-textiles require novel solutions to integrate electronics and textiles for improved recyclability. Since electronic components interfere with textile recycling if they are not detected, it is advisable to dispose e-textiles at electronic waste collection points.

In order to govern the product design and the e-textile waste treatment, an extension of the scope of the WEEE Directive appears to be fruitful. For example, the definition of small equipment in the WEEE Directive can be adjusted to include e-textiles. The legal frameworks for sustainable, circular product development are also established at EU level by the Ecodesign Directive 2009/125/EC. The scope has so far been limited to energy-related products. Both textiles and products with electrical circuitry and consequently e-textiles are not addressed. Again, expanding the scope of the Ecodesign Directive might facilitate the design of e-textiles for efficient recyclability.

The lack of financially viable business models in recycling compared with low-cost supply of new products impedes the recycling rate. Approaches to integrate the end-of-life treatment in the product costs and distribute the costs partially to the responsibility of the producers may contribute to the development of efficient recycling processes. However, sustainable business models for increasing recycling require definitely further exploration.

Conflict of interest

The authors declare to have no conflict of interest.

Thanks

The authors thank the participants of the survey for their contribution.

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