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Paving the road to a circular textile economy with AI

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Abstract: The textile industry has a detrimental impact on the environment and faces challenges to meet climate and environmental goals. The core problem is its linear system where only a small fraction of used garments is reused or recycled. To facilitate recycling of textiles, a sorting method is proposed that provides the necessary information about a garment to sort it into the appropriate recycling channel. Current methods have difficulties identifying garments polluted by chemicals used during dyeing and finishing which hinder recycling into new high-quality fibers. In this concept paper, the Circular Textile Intelligence (CRTX) project is outlined which addresses the central problem of linear structures in the textile industry. A spectroscopy and AI-based method for textile sorting will enable more informed decisions about optimal reuse and recycling channels, thus closing the loop. It will build upon a material database containing information about materials, textiles, dyes, finishings, and unwanted hazardous substances.

Keywords: Circular Economy; Textile Recycling; Chemometrics; Spectroscopy; Artificial Intelligence; Neural Networks

1 Introduction and background

The textile industry has a major negative impact on the environment, due its incapacity of reusing raw materials, as well as its extensive use of pollutants. The total greenhouse gas emissions from textile production currently exceed those of all international flights and shipping combined, at 1.2 billion tons of CO_2 eq. per year.[14, 5]

The textile industry's central problem is its primarily linear production pattern. Currently, over 100 billion garments are produced annually worldwide, predominantly from virgin raw materials (> 97%). At the end of their use cycle, these are generally disposed of in landfills or incinerated (87%) or mechanically recycled to a lower value (downcycling) (12%).[2] Less than 1% is recycled using innovative recycling processes so that it can be used again as a raw material for new garments.[2] In this context, fiber-to-fiber recycling would save the extraction and production of virgin fibers and prevent the waste of resources

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through landfill and incineration. Fiber regeneration would have been technically possible for several years through chemical recycling processes[13, 3]. However, it requires very precise information about the composition of the garments to be recycled, which cannot be determined by current sorting methods. Fiber-to-fiber recyclers have very specific ban lists on certain chemicals, fibers and material blends that must not be contained in the feedstock.[1]

Contamination and pollutants pose a serious problem for existing fiber-to-fiber recycling processes. For example, coatings based on fluorocarbons, such as those found in impregnated outdoor materials, pose a major problem for chemical recycling processes – even in very low concentration.[1] Also, a separation or exclusion of certain dyes is required by some recyclers. This limits the range of suitable feedstock to either well characterized production waste (pre-consumer) or easily identifiable garments with known characteristics (e.g. indigo dyed blue jeans).

According to the German Federal Environment Agency (Umweltbundesamt), up to one kilogram of harmful chemicals is used per kilogram of processed textiles during textile finishing.[16] A large proportion of the textile auxiliaries subsequently end up in wastewater[4], having detrimental effects on the environment. As stated by Greenpeace e.V., the textile industry is responsible for approximately 20% of the discharge of organic pollutants into water bodies. Some of these substances are difficult to degrade and can only be reduced to a limited extent in biological wastewater treatment plants.

Conventional sorting plants focus on the extraction of reusable garments to be sold to the second-hand market. A small portion of the remaining textiles undergoes material specific sorting for textile recycling, which is predominantly conducted through haptic recognition. Better results could be enabled by optical detection with near infrared (NIR) spectroscopy, which is currently tested in pilot sorting plants.[18, 3] These sorting plants focus on the detection of cotton, polyester and wool and do not identify possible contaminants. Here, the vision for a project is presented, which aims to reliably detect the material composition and contamination of used textiles to enable fiber-to-fiber recycling. A multispectral approach will be combined with Artificial Intelligence (AI) by using convolutional neural networks (CNN) for the material classification. Used clothing contaminated with harmful substances could be sorted out and sent for hazardous waste recycling, thus preventing contamination in future garments. Furthermore, a contaminant analysis in the recycling process provides a concrete and reliable source on consumer exposure to contaminants. Guidelines and decision-making principles for environmental protection could be derived from the analyses.

2 Goal of the Project

The overarching goal is to close the missing gap that exists in textile recycling, thereby enabling a more sustainable textile industry. In order to capture all facets of this diverse challenge, the project focuses on three parts: (i) optimizing the reuse of garments (small cycle) by classifying the type of second hand garments via computer vision, (ii) enabling textile fiber recycling (large cycle) and (iii) identifying hazardous substances in textiles. Achieving these three aspects corresponds to several sustainability dimensions and would have significant impact at the social and economic level. The content of the remaining paper focuses on parts (ii) and (iii), because an extensive description and discussion of part (i) would exceed the scope of this report.

The aim of part (ii) of the project is to demonstrate how a spectroscopy-based automated detection that is backed by an AI-classifier can identify raw materials and pollutants to enable a sustainable circular economy for textiles. In order for sorting to be optimized, relevant information from the garments will be identified through the development of a combined approach merging spectroscopic analysis and an appropriate AI-based classification.

The project continues to address the issue of pollutants in textiles (subproject (iii)), both in terms of recycling requirements and environmental targets. On one hand, a mapping and market overview of commonly used chemicals and their influence on recyclability will be developed within the scope of this subproject. On the other hand, an algorithm will be developed that compares the chemical list of textiles with recycling specifications and environmental guidelines. The results of this working part will then be made accessible to the spectroscopy AI as new features. Considering current environmental targets and including possible alternatives for harmful substances, project results are envisioned to lead to changes in the product design as actions for manufacturers. In the long term, this approach should be able to identify and decrease the use of pollutants from the textile industry's material flows.

3 Current advances in AI and spectroscopy for textile analysis

Researchers can choose from a wide variety of spectroscopic methods to investigate the characteristics of a textile sample. Near infrared (NIR) spectroscopy is able to distinguish different fiber materials of textiles and is indeed suitable for analysis of a large sample set. Automated sorting of used clothing based on material composition has been tested using visible and near infrared spectroscopy (VIS-NIR spectroscopy) and has succeeded in separating textiles by color and material.[17, 18, 3] However, there are certain requirements of high-quality recycling processes that this technology cannot meet.[20] One shortcoming of the mentioned sorting technologies is their inability to analyze other characteristics, especially finishings and contaminants.

Other methods, such as nuclear magnetic resonance spectroscopy (NMR), chromatography and mass spectrometry, can deliver exhaustive and reliable information about textiles samples but are not suitable for use on a sorting line due to very high efforts in terms of sample preparation and experimental setup.[12]

Another method that is used to analyze textile samples in criminal forensics on a laboratory scale is Raman spectroscopy in the VIS and NIR range.[15, 7] Raman spectra yield information about the fiber type as well as dyes and other finishings. Publications show that the spectra provide sufficient information for optimized recycling.[12, 6] However, the common interference of fluorescence with the Raman signal is an obstacle that needs to be tackled in the future.[12] Raman spectroscopy is advantageous as its signals have a high degree of information, which allows very accurate differentiation of materials. Compared to NIR spectroscopy, materials have a significantly lower cross-entropy due to the distinctive and discrete spectral peaks in the signal.

Machine learning methods are becoming more and more popular for the analysis of Raman spectra. Liu et al. [8] highlighted the use of convolutional neural networks (CNN) for the purpose of material identification in Raman spectra. The approach shows that CNNs, unlike traditional chemometric methods (e. g. principal component analysis (PCA)), can effectively identify substances without the need for complex preprocessing, even with fluorescence background from the spectra. Several recent studies report on the advantages of using a CNN for analyzing Raman spectra compared to other methods such as partial least square regression [21] and conventional Raman processing methods [19].

In relation to the project, the work of J. Luo et al.[9] should be highlighted, which aimed to analyze cotton purity combining NIR Raman spectroscopy and AI analysis. By using a simple random forest model, a decision tree was generated that can detect the contamination of cotton with polyester and thus verify the manufacturer's claims of the fiber composition. The focus of the study is on quality assurance of cotton textiles, some of which are stretched with synthetic fibers due to cost pressure.

4 A spectroscopy- and AI-based sorting method for fiber-to-fiber recycling

By combining multi-spectral analysis tools, a reliable optical detection method for identifying the material composition and contamination of used textiles is to be created. The combination of several spectral ranges will enable sorting in compliance with the requirements of fiber-to-fiber recycling. NIR spectroscopy provides broad and continuous spectra that allow for coarse presorting based on the fiber material. On the other hand, Raman spectra in the visible and UV range consist of distinct and discrete lines that are more difficult to interpret but allow for much finer material specific classifications. Raman spectroscopy can therefore produce a molecular fingerprint of the textile and can provide information about the occurrence of substances that have been explicitly excluded from the list of substances permitted for the recycling process.

Within the scope of this project, a neural network based classifier will be developed to classify a large amount of different materials. This approach is believed to be superior to classical chemometric analysis methods such as principal component analysis (PCA). In particular, the vast amount of possible substances can increase the dimensionality of PCA. This leads to a large number of configurations where those with low eigenvalues can be missed even if they are essential to represent the original data. Instead, neural networks have already been successfully applied outside of the textile sector for the interpretation of Raman spectra and have proven their worth as an analysis tool for chemical fingerprinting. In particular, the use of different data sources is important to gain maximum reliability. In addition to the multi-spectral data, the data set will be enriched by garment type information from subproject (i) determined via computer vision. Based on this extensive and diversified data set, the AI will classify the material composition and estimate the pollutant load in order to make decisions regarding the appropriate recycling channel.

In contrast to conventional spectroscopic analysis routines, it is not the quality of the fit that is crucial here, but the certainty of unique classified features. For example, recyclers have different requirements for the accuracy of component determination. Some recyclers allow mass fractions of elastane in the single-digit percent range in their processes, but must be able to exclude other contaminants in the range of a few ppm. A conventional method requires very high accuracy over the entire spectrum to solve the task and achieve sufficient convergence of the fit to make a confident conclusion. A deep neural network can be used to consider the existing requirements of the recycler. Hence, the approach considers the expectations of the results already for the analysis. It integrates the classically separated processes of data analysis and result interpretation into a holistic spectroscopy. In addition, mutually exclusive components such as material-specific staining can be taught. Thus, the strong correlations and anti-correlations of features are taken into account. Furthermore, exclusionary substances such as fiber-specific dyes and finishings serve to resolve degeneracies of the spectral components and make the method more robust.

The certainty of the estimation takes an integral part and decides whether a textile has been classified with sufficient accuracy. Here, the limits defined by the recycling methods do not have to be met per individual garment, but only per sorting unit (e.g. container or bale). In this way, a stochastic approach can be used to achieve a maximum recycling rate with optimized utilization of the limit values. In the case of an uncertain estimate, the system can decide to measure again or to adjust the integration time of the measurement independently in order to improve the signal-to-noise ratio. The necessary integration time can be used as feedback to estimate the optimal integration time depending on previous knowledge (e.g. absorption coefficients from UV-VIS-NIR pre-characterization). This results in a time-optimized evaluation. If the signal-to-noise ratio is already maximized without sufficient classification, this may indicate a still unknown substance. For resolution, the textile can be directed to further laboratory analysis (e.g. chromatography or NMR). The results of this analysis are used as a feedback for the evaluation. In this way, the system continuously learns previously unknown Raman spectra and improves its recognition performance over the initially learned spectra from the development phase.

The data on contaminants derived from sorting will also be used for monitoring compliance of the textile industry with the REACH regulation[10] or stricter standards such as ZDHC[22]. This way, real pollutant levels in the textile cycle can be identified and reduced, independently of manufacturer data, in order to improve the safety of textiles in the long term. Textiles that are not REACH compliant, e. g. those that originate from non-EU markets or were produced before the REACH implementation, are sorted out. Similarly, textiles contaminated by use (e. g. contaminated work clothing) can be recycled as hazardous waste, so that harmful substances are successively removed from the textile material cycle.

5 Outlook

The shift to a circular economy is a significant building block for achieving the UN Sustainable Development Goals (SDGs) and will contribute to solving current ecological challenges. The results of this project aim to create the necessary tools to foster a systematic change from linear to circular practices in the fashion industry. The textile industry has the potential to act as a role model in this regard, as 60 million people worldwide are professionally involved in textile production[11]. Since every person is wearing clothes, everyone can relate to the challenges of this industry and might even be affected personally. This makes the topic particularly tangible and shows the possibility of direct influence on the consumer side, thus creating the potential to spread the concept of circularity to other sectors.

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