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Near-infrared-based sortability of polyester-containing textile waste

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ABSTRACT

Through textile recycling, resources can be saved, and landfilling can be avoided. However, determined input streams are needed for high-quality recycling processes. The aim of this study is to investigate the detection, prediction and sorting of polyester-containing textile waste using near-infrared spectroscopy. In experimental trials, polyester-containing textiles with different fibre blends are scanned, and the spectra are recorded. The results are evaluated in a linear regression model and transferred to an industrial-scale sorting plant. Due to the different peaks in the spectra of the investigated fibre types and a visible correlation of the absorption intensity between the blend ratios, the use of NIR spectroscopy is very promising for application in the sorting of polyester-containing textiles.

List of abbreviations

MAE	Mean absolute error
QCI	Quantitative Chemical Imaging
CO	Cotton
CV	Viscose
EL	Elastane
PET	Polyester
PAN	Acrylic
PA	Polyamide
NIR	Near-infrared
SBS	sensor-based sorting
DO	D 1 (1

- RQ Research question
- WO Wool

1. Introduction

1.1. Textile market

The demand for textiles and clothing is growing rapidly due to an increase in average wealth and the growth of the world population (Ellen MacArthur Foundation, 2017; Janmark et al., 2022). Clothing production alone almost doubled between 2000 and 2015 (Ellen MacArthur Foundation, 2017), and in 2022, 126 Mio. tonnes of fibres were produced globally. Of these, approximately 74 wt % is accounted for by man-made

fibres. Polyester fibres account for 54 wt % of the global fibre production, whereas natural and cellulosic fibres, such as cotton or viscose, make up 32 wt %. Polyamide fibres account for 5 wt % and 9 wt % consist of other synthetic fibres such as polypropylene, acrylics or elastane (The Fiber Year GmbH, 2022). As a result of fast-fashion trends, garments of lower quality and at cheaper prices are purchased and thrown away after a short use phase (Ellen MacArthur Foundation, 2017).

One of the negative consequences of high clothing consumption is the negative environmental impacts caused by textile production and textiles ending up in the environment at their end-of-life. The production and consumption of textiles lead to water use, chemical pollution and CO₂ emissions (Niinimäki et al., 2020). Synthetic fibres, which make up a large part of the market, are derived from fossil resources (The Fiber Year GmbH, 2022). As clothing and textiles production and consumption increases, so does the number of used textiles (Janmark et al., 2022).

After the use and/or reuse of clothing, 73 wt % of the garments are incinerated or landfilled, while only 12 wt % are used for cascaded recycling and less than 1 wt % are recycled into new clothing (Ellen MacArthur Foundation, 2017). Through textile recycling, resources like water, energy and chemicals can be saved, and landfilling can be avoided (Berg et al., 2020). Since polyester fibres make up more than half of the world's fibre production, polyester-containing textiles are the focus of this work.

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1.2. Textile production and fibre blends

With the help of material blends, textile products can be functionalised and gain a wide range of properties. Therefore, textiles often consist of a high diversity of materials. Common blends of natural and man-made fibres are, e.g., made up of polyester (PET) and cotton (CO), also referred to as polycotton (PET/CO). While cotton offers good moisture management and a soft touch, polyester fibres are added to make products more durable and cheaper. Furthermore, polyester fibres can be blended with elastane (EL), viscose (CV), polyamide (PA), wool (WO) or acrylic (PAN) to give the textile product the desired properties. However, not all properties can be achieved by fibres and the textile structure alone. Therefore, surface coating can be applied, or layers of different textiles can be sewn together. Further, in manufacturing, haberdashery like buttons, zippers, or evelets are added. These material combinations pose a challenge for recycling and require different treatment than other plastic products such as packaging. Accordingly, textiles require adapted sorting and recycling methods. (Gries et al., 2018; van Duijn et al., 2022; Veit, 2023)

1.3. Disposal and recovery of textile waste

For textile waste, mostly mechanical tearing processes are currently used. In this process, the textiles are shredded and fed into a tearing machine, which consists of two or more counter-rotating rollers. The textile structure is opened so that the fibres lie freely at the end of the process. The tearing stress shortens the fibres. The shortened fibres are often used to produce downstream products such as insulation materials. Furthermore, shortened fibres can be (partly) added to primarily produced fibres to produce high-quality products. (Damayanti et al., 2021)

Other recycling processes for polyester textiles include thermomechanical recycling (regranulation), physicochemical recycling (solvent based separation), or chemical solvolysis processes (depolymersation) such as hydrolysis or glycolysis (Cornier and Pursche, 2023). In the regranulation process, synthetic fibers or textiles are melted down and regranulated. Synthetic monomaterials are required for the production of high-quality regranulates (Sujatta et al., 2023). The solvent based separation is designed to separate different polymers from each other. In this process, the desired polymer is dissolved selectively, separated and precipitated using solvent. The other materials remain undissolved. In the solvent based separation, the molecular chains of the polymer remain intact (Sherwood, 2020), while in chemical solvolysis, the molecular chains are broken down into monomers. After this depolymerisation, the monomers are separated and precipitated through, for example, crystallisation or distillation. In PET hydrolysis recycling, therephtalic acid and ethylene glycol can be recovered while cotton fibres can be separated and recycled further (Bengtsson et al., 2022; Peterson et al., 2022). In PET glycolysis, BHET is recovered. In the literature, only textile feedstocks with a high PET-content are described (Barot and Sinha, 2015; Guo et al., 2021; Li et al., 2020). While some processes are better for recycling one component, others are specifically designed to recycle blended materials. Even though the processes are very different from each other; all require defined feedstocks as input material. To produce defined feedstocks, accurate sorting of textiles plays an important role.

1.4. Near-infrared spectroscopy

Near-infrared (NIR) light is part of the electromagnetic spectrum of light and includes wavelengths between 780 nm and 2500 nm. In this study, SI units wavelength (nm) are used.¹ NIR spectroscopy enables the non-destructive analysis of molecular compositions and is used for

surface analysis (Ozaki et al., 2021; Skoog and Leary, 1996). Even though NIR spectroscopy has been used for the analysis and sorting of textile waste (Refashion, 2023; Sysav Industri AB; van Duijn et al., 2022), little information can be found in the literature about the achievable accuracy of detecting different fibre materials and blends. (Zhou et al., 2019) have analysed the identification of textiles consisting of only one type of fibre using NIR spectroscopy. The investigation resulted in a high recognition rate and the finding that individual fibre types like cotton, polyester, polyamide, acrylic, silk and wool can be clearly distinguished based on the NIR spectra. The differentiation of the spectra of dyed polycotton blends was analysed by (Rodgers and Beck, 2009). Using different regression models, measures of determination between $R^2 = 0.949$ and $R^2 = 0.988$ were calculated for the correlation of the NIR spectra with the textile composition. (Li et al., 2021) analysed the NIR-sensor-based sorting of textiles of different fibre types and blends. By scanning and training 593 samples and sorting 299 textiles, a recognition rate of 99 % was determined. However, the recognition rate does not refer to a specific composition of a textile but whether it is sorted into the correct category, for example, CO or PET/WO. This means that no statement can be made about the recognisability of blend ratios. Furthermore, no literature was found on the identification of elastane in fibre blends using NIR.

1.5. Aim and research questions

In this study, the results of the different publications are expanded. In addition to polycotton blends, other PET blends with elastane, viscose, acrylic, wool, and the three-fibre blend of polycotton and elastane are investigated. Furthermore, the findings are used to sort textile waste in industrial scale. Four research questions (RQ) shall be answered:

- **RQ1:** How accurately can the polyester content in polyester-cotton textile blends be detected and predicted using NIR spectroscopy?
- **RQ2:** How accurately can polyester-containing textiles with different fibre blends be differentiated and sorted using NIR spectroscopy?
- **RQ3:** What influence do post-consumer effects and other impurities have on the detectability?
- **RQ4:** How can the findings of this study be transferred to an industrial scale?

2. Material and methods

2.1. Textile samples and solubility tests

The most common fibres and polyester-containing blends in clothing (Refashion, 2023) are considered in this study. The samples were bought in various shops in Germany and online. Since a large amount of textile labels do not state the correct composition of the textile (Wilting and van Duijn, 2020), all samples used in this study are analysed. For the quantitative chemical analysis of various mixtures of fibres, ISO 1833 is used (ISO 1833). The different materials are dissolved selectively after each other from 1 g of the textile product. Elastane was dissolvent in Dimethylacetamide in accordance with ISO 1833-20 (ISO 1833-20). For the cellulose component 75 % sulfuric acid was used according to ISO 1833-11, and for polyamide, ISO 1833-7 was applied using 80 % formic acid (ISO 1833-11, ISO 1833-7). In addition to the described samples, we were provided with the material database with further textile samples that were tested using the same norms. With this database, the tested samples are supplemented with samples consisting of PET/WO and PET/PAN blends and further PET/CO and PET/CV blends (International Organization for Standardization, International Organization for Standardization, International Organization for Standardization, International Organization for Standardization).

¹ Wavelength (λ) can be converted into wavenumbers ($\tilde{\nu}$) using $\tilde{\nu} = \frac{1}{4}$

2.2. NIR spectroscopy trials

To determine the detectability of different textile compositions, a sensor test rig was set up, and the settings were adjusted for adequate detection of the textile samples. Fig. 1 shows the experimental setup. For the laboratory-scale experiments, a EVK HELIOS EQ32 sensor from EVK DI Kerschhaggl GmbH, Raaba, Austria, hereinafter referred to as *sensor*, in a spectral range of approx. 930 nm to 1700 nm was used. The spectral resolution of the sensor is 3.1 nm/pixel, and the spatial resolution is 1.25 mm/pixel. It has an integrated classification system. The sensor is mounted on a frame. One halogen spotlight with a power of 400 W is used as the emitter. For the background, a black stone tile is used.

The sensor is connected to a computer that accesses the data of the spectrometer using the software EVK SQALAR, software version 5.2.X. The software creates the spectra and offers possibilities to analyse and compare the data. The first derivative of the reflectance data is calculated by the program for analysis. The derivative is better suited for analysis because the changes in reflectance intensity are better revealed (Chen et al., 2021).

To teach the software of the NIR sensor with the created material database, all textile samples are scanned. To create a spectrum of the sample, a large and well-illuminated area of about 20 cm² is selected from the image. The software SQALAR then calculates the smoothened and normalized first derivative from the reflection values received, which is displayed in the software as a graph. Quantitative chemical imaging (QCI) is an analysis tool that is included in the SQALAR software and which is used to obtain information on the correlation of NIR spectra and peaks. QCI uses the extent of specific wavelength peaks to determine the share of the material that induces this peak. The QCI function in the SQALAR software automatically selects the most relevant wavelength range for the respective distinction. The recorded spectra are saved with a reference to the composition of the sample.

3. Results and discussion

3.1. NIR spectroscopy of polyester, cotton and polycotton textiles

The blend of polyester and cotton is the most common fibre blend in textiles. The differentiability of the blend ratios with an NIR sensor is analysed based on the differences in the spectra and quantitative chemical imaging (QCI).

3.1.1. Polyester

Polyester is polymerized from the monomers ethylene glycol and terephthalic acid. The characteristic peaks of the NIR spectrum of polyester can be seen between 1100 nm and 1150 nm and around 1630 nm - 1680 nm. C-O bonds from secondary alcohols, such as ethylene glycol, can cause second overtone vibrations, which lead to peaks between 1087 nm - 1124 nm (Ozaki et al., 2021). In addition, absorptions

at the wavelength of 1130 nm can result from the third overtone vibration of CH_2 bonds (Cucuzza et al., 2021). The peak around 1648 nm can be traced back to stretching of the C = C double bonds in the aromatic ring of the terephthalic acid of the polyester and/or C = O bonds in the polymer. Both bonds can also cause absorption around 1648 nm to 1680 nm. Furthermore, in the range of wavelengths between 1650 nm and 1800 nm, first overtone vibrations of the C—H bond may be responsible for absorption. (Merck Group, 2023; Ozaki et al., 2021)

3.1.2. Cotton

Cotton mainly consists of cellulose, which is made of glycose units. The most characteristic peaks of the cotton spectrum are at 1355 nm, 1416 nm, 1470 nm, and 1605 nm. In the wavelength range of 1400 nm to 1500 nm, first overtone oscillations of O—H bonds of the glucose may be responsible for the absorption (Metrohm AG, 2013). A peak in the raw spectrum is at about 1550 nm, as this is where the transition between the low point at 1416 nm and the high point at 1605 nm is located. The first overtone vibration from the O—H bonds contained in the cotton is responsible for this increased absorption at 1550 nm (Miller, 1991).

3.1.3. Polycotton

Fig. 2(a) shows an overview of the normalised first derivative of the raw spectrum, in the following called *spectrum*, of 30 samples with different compositions covering the entire spectrum from 100 % PET and 0 % cotton to 0 % PET and 100 % cotton. All textile compositions used in this graph can be found in Table S1 in the supplementary material. The characteristic peaks of polyester and cotton are both visible in the NIR spectra of the blended materials. It is clearly visible that there is a correlation in absorption intensity between the compositions.

For this purpose, 39 NIR spectra are added to the QCI algorithm, which reflect the compositions between 100 % PET and 100 % CO. The compositions of the samples can be found in Table S2 in the supplementary material. Not all spectra discussed in the previous chapter are included. Spectra that show a very large deviation from other spectra were noticed as outliers and, therefore, not used in the QCI. For each uploaded spectrum, the SQALAR software is taught the determined PET content. The software creates a linear regression model that calculates the correlation between the determined compositions and the spectra, see Fig. 2(b). Each point represents a spectrum and the taught compositions, or setpoints, can be recognised by the values of the x-axis for each point. It is assumed that deviations are caused by dyes or a certain type of textile surface. The mean absolute error (MAE) represents the difference of the setpoint from the measurement (Devore, 1987; Willmott and Matsuura, 2005). The MAE overall data value is about 4.0 %, i. e., on average, there is a deviation of \pm 4.0 % of the predicted and true cotton share.

The coefficient of determination (R^2) is used in statistics to assess the goodness-of-fit of a regression. It indicates the dispersion of the data



Fig. 1. Experimental setup of the trials.



Fig. 2. Mixed polyester-cotton spectra. (a) Spectra from 0/100 % PET/CO to 0/100 % CO/PET and (b) linear regression model with 39 polycotton spectra.

within a linear regression model. If $R^2 = 1$, the data can be described with a linear function. If $R^2 = 0$, no linear relationship can be detected. The value indicates how well a model is suited to describe the data. (Devore, 1987; Fahrmeir et al., 2022). In SQALAR, the coefficient of determination can be used to estimate how well the spectra correlate in a linear way. The present value $R^2 = 0.975$ indicates a very high suitability of the linear regression model to describe the data as well as a very high correlation of the data with each other. Based on the low MAE (4 %) and high R^2 -score, it can be stated that a differentiation of textiles according to different polycotton blends based on the NIR spectra is possible with high accuracy. By using the regression model, further spectra of polycotton textiles, whose specific compositions have not been taught, could also be classified. This can be used for industrial sensor-based sorting (SBS) of used textiles.

3.2. NIR spectroscopy of other fibre blends

In this chapter, other fibre types such as elastane, viscose, acrylic and wool, as well as blends of these fibres with polyester, are described. The spectra of monomaterial textiles made of polyester, cotton, elastane, viscose, acrylic, wool, and polyamide are displayed in Fig. 3

3.2.1. Polyester-elastane

Elastane fibres are usually only present in small amounts in textiles. The fibres can be added during the production of textile fabric or during the production of the yarn, for example as core or winding yarn, making them hard to detect (Veit, 2023). Elastane is PU-based and can be made of different monomers, making it difficult to assign certain peaks (Gries, 2005). Pure elastane fibres show several peaks, depending on the



Fig. 3. Comparison of spectra from fibres or textiles made of 100 % (a) polyester, elastane, acrylic, polyamide, and (b) cotton, viscose, or wool.

Elastane composition, as shown in Figure S3 in the supplementary material. Fig. 4(a) shows spectra of textiles made of polyester and elastane, as well as pure polyester and elastane textiles. The peak of the spectra of polyester textiles seems to be less intense with elastane.

The QCI is used to check whether there is a linear relationship between the spectra of 86 % - 100 % polyester (equivalent to 14 % - 0 % elastane) textiles. A list of spectra used can be found in Table S4 in the supplementary material. The coefficient of determination of $R^2 = 0.95$ shows that there is a linear relationship between the spectra as a function of increasing elastane content. The MAE calculated over 13 spectra is 0.75 %, which seems low compared to the average mean error of 4.0 % calculated for the polycotton blends. This can be attributed to the smaller investigated range of PET contents between 86 % and 100 % for the polyester-elastane blends. The linear regression shows that different elastane contents can be detected in polyester textiles. The linear regression model of the PET-EL spectra is shown in Table S5 in the supplementary material. To determine the influence of the processing of the elastane fibre on the spectra, it would be necessary to work with a larger database.



Fig. 4. Comparison of spectra from textiles blends made of (a) polyester-elastane with 1–14 % elastane, (b) polyester-viscose with 50–87 % viscose, (c) polyesteracrylic with 20–18 % acrylics, and (d) polyester-wool with 52–80 % wool. An overview of all used compositions can be found in S6.

3.2.2. Polyester-viscose

Viscose, like cotton, consists of cellulose. However, viscose has a different crystal structure, as well as a lower degree of polymerisation. Fig. 4(b) shows the NIR spectra of textiles consisting of blends of polyester and viscose, as well as spectra of textiles made of only polyester or viscose. The peaks at 1355 nm and 1416 nm are strongly developed in both the cotton spectrum and the viscose spectrum. At other points, the spectra of cotton and viscose differ, for example, the peak at 1470 nm is missing in the viscose spectrum, as shown in Figure S7 the supplementary material. This is relevant because in some recycling processes, only cotton without viscose is desired. The 48 %/52 % polyester-viscose spectrum is the only spectrum in which the polyester peak at 1648 nm is fully pronounced. The polyester contents of 31 % and less do not show a fully pronounced polyester peak. The different polyester and viscose contents can be recognised by the shift in peak intensity, similar to the observation in polycotton blends.

3.2.3. Polyester-acrylic

Acrylic, or polyacrylonitrile, fibres are often used in blends with other materials and used in leisure wear or artificial fur (Veit, 2023). The most intense peak of the spectrum of PAN is at the wavelength 1680 nm. The spectra rise sharply after the minimum, and an extreme point is found in the raw spectrum around 1700 nm. It is assumed that this increased absorption may result from the overtone oscillation from the N=C triple bond, but no literature is found to confirm this assumption. Around 1185 nm, there is a turning point of the spectrum, which is also an extreme point of the raw spectrum. This absorption at the wavelength 1185 nm may result from the second overtone oscillation of C—H bonds. Ozaki et al. also give the second overtone oscillation of 1185 nm - 1195 nm (Ozaki et al., 2021). Weaker absorptions can be seen in the wavelength range from 1350 nm - 1450 nm.

Fig. 4(c) shows the spectra of different textiles consisting of blends of polyester and acrylic fibres, covering polyester contents of 18 % - 80 %. The spectra of the textile with the highest polyester content show the weakest peaks between 1350 and 1450 nm. Furthermore, this spectrum shows a polyester peak at 1648 nm, which is next to the acrylic peak at 1680 nm. With increasing acrylic and decreasing polyester content, the peaks typical for acrylic become more pronounced. The spectrum with the lowest polyester content of 18 % is the only one to show a polyester peak that is not completely pronounced. Based on the visually recognisable correlation of the spectra, a linear regression model can presumably be used to represent the data, and different polyester-acrylic contents can be separated from each.

3.2.4. Polyester-wool

Several characteristic peaks are recognisable in the spectrum of wool textiles at 1170 nm, 1405 nm and 1680 nm. Similar to the cotton fibre, the first overtone oscillations of OH bonds in the range from 1400 nm to 1550 nm are responsible for the increased absorption of the NIR light. However, the chemical structure of wool molecules is complex, and the absorptions and resulting peaks can only be guessed. Fig. 4(d) shows the spectra of polyester-wool blends as well as wool and polyester. With increasing polyester content, the wool peak at 1405 nm becomes visibly weaker. The polyester peaks at 1648 nm and 1675 nm are fully pronounced at the PET contents of 36 % and 48 %. The coefficient of determination is $R^2 = 0.965$, though it is not possible to recognise a linear correlation for the entire range of polyester-wool blends based on the few spectra available.

3.3. NIR spectroscopy with contaminations

Besides the trials with different fibre blends, other aspects are also considered in this study. This includes the investigation of the influence of moisture and shadows on the textile. Furthermore, the influence of thin and sheer items is tested using four textile samples. The textiles are tested as single layers and multi-layers. The multilayers are tested by manually folding the samples to the desired thickness. No visible deviation can be noted between the spectra of single and multilayers of the shear textiles.

3.3.1. Moist and wet textiles

To investigate the sensibility of water in the NIR scanning process, a polycotton sample is scanned several times with added water content. As the moisture content of the textile increases, the cotton peak at 1416 nm shifts towards the water peak at 1390 nm, see Fig. 5(a). In addition, the intensity of the other peaks decreases. First overtone vibrations of the water molecules are responsible for the absorption of the wavelength at 1450 nm. It is likely that moist textiles can still be detected and sorted using NIR. For this, wet textiles must be taught to the software too. To efficiently include moisture in the training process, further research the influence of moisture on the different fibre blends must be done in the future.

3.3.2. Wrinkels and shadows

Upon garments falling onto the conveyer belt during automated sorting, some winkles may occur. To investigate the influence of wrinkling on the spectra, some wrinkles are manually simulated on one sample. Fig. 5(b) shows the spectra of a polyester-viscose textile in different levels of wrinkling. The more wrinkled the textile is, the more pronounced the viscose peaks become. The textile can still be recognised as a PET and viscose blend if it is heavily wrinkled but no longer with the correct composition. A more detailed analysis of the influence of shadows is recommended for future research.

3.4. Discussion of results from laboratory trials

Due to the absorptions at different wavelengths, all scanned fibre types can be differentiated from each other based on the NIR spectra. Furthermore, based on the conducted trials it is also assumed that different contents of polyester in blended textiles can be identified with only minor deviations of a few percent. Table. 1 shows the wavelength ranges relevant for an identification of the most important fibre types, related to the first derivative of the raw spectrum. The wavelength ranges were determined based on the characteristic peaks and the respective environment.

It is noticeable that the PET peaks in the spectra of the examined blends show the highest pronunciation compared to the other peaks for PET contents between 30 - 100 %. Only for PET contents of less than 30 %, the peaks in the spectra of the other component show the highest intensity. All blends can be described by a linear regression model. It is assumed that the correlations in the blends are high enough to be able to assign textiles to a fibre composition with a deviation of 5 % on average, based on the NIR spectrum. The spectra of textiles are influenced by additives, dyes and the type of textile surface so that uncertainties are included in the spectra.

3.5. NIR-based sorting trials at industrial scale

The industrial-scale trials are carried out in a plant consisting of a feeding unit, different conveyor belts, a detection/sorting unit, and a discharge unit, see Fig. 6. The sorting unit contains the NIR sensor and the NIR source. For the NIR sensor, an AUTOSORT by TOMRA Sorting GmbH, Mülheim-Kärlich, Germany, is used. Textiles are fed manually onto the conveyor belt.

The same spectra are taught into the software as in the laboratory trials and target sorting categories are defined. In the software, each pixel is assigned to one of the previously created categories based on the spectrum. An overview of the chosen target categories and the order of sorting are shown in Figure S8 in the supplementary material. If the scanned textile is identified as belonging to the target category, the compressed air nozzles at the end of the conveyor belt are activated, and



Fig. 5. Spectra of a polyester-cotton textile with different moisture levels (a) and a polyester-viscose textile with different degrees of wrinkles.

Table. 1	
Relevant wavelength ranges for identifying a fibre type.	

Fibre type Relevant wavelength ranges for identifying [nn	1]
Polyester 1120–1150, 1645–1680	
Cotton 1350–1480, 1605	
Viscose 1350–1420, 1505	
Wool 1120–1160, 1400–1500, 1680	
Acrylic 1150–1200, 1680–1700	

the textile is ejected. Textiles that are not identified as a target fraction, called drop, fall down at the end of the conveyor belt and land in another container.

For the sorting trials on an industrial scale, around 430 kg of textile waste from Aachen, Germany, provided by WABe e. V. Diakonisches Netzwerk Aachen, were used. The textiles were sorted beforehand, and reusable textiles that can be sold in the WABe shop were taken out. Furthermore, multilayer textiles, shoes, bags, and other materials, which made up 26 % of the 430 kg are taken out manually. This share is not sorted by the SBS unit. The remaining 320.6 kg of textiles can be sorted into pre-defined categories, which can be found in Figure S9 in the



Fig. 6. Concept for sensor-based sorting of textile waste.

supplementary material. The presented concept for sensor-based sorting of textile waste is promising. With a conveying speed of around 3 m/s, the textiles only take 0.1 - 0.3 s between the sensor and ejection unit. However, various challenges occur that have to be considered when sorting garments and home textile waste on an industrial scale:

- Singular and flat placement of the textiles must be ensured for the NIR sensor to scan the textiles correctly.
- Due to their size and weight, large textiles, such as bed linen, require more powerful compressed air nozzles to be ejected compared to conventional packaging waste.
- Multilayer textiles cannot be sorted correctly with the proposed setup since the penetration depth of NIR radiation is only about 150 μ m (Chen, 2022). Furthermore, it has to be ensured that the core component of a core yarn, often elastane, is detected properly for the same reason.
- Haberdashery (for example, buttons, zippers, labels) are often made of a different material than the textiles and shall possibly be removed before recycling in a pre-processing step (Janmark et al., 2022). If removal is necessary, they have to be detected by the NIR sensor.

4. Conclusion

In this study, the technical feasibility of detecting, predicting, and sorting polyester-containing textiles has been investigated. The results show that the polyester content in polycotton or in different blends of polyester in combination with elastane, viscose, acrylic or wool can be identified with state-of-the-art NIR technology. The characteristic peaks of the individual fibres are also visible in the spectra of the blended materials. The correlation in absorption intensity between the compositions makes it possible to differentiate between blend ratios. Applying a linear regression model, the coefficient of determination was calculated for n = 39 polycotton spectra ($R^2 = 0.975$) and n = 13 polyesterelastane spectra ($R^2 = 0.95$). It is determined that the recognition of the textile composition in polycotton textiles based on an NIR spectrum is possible with an MAE of approx. 4 %. Furthermore, wrinkles or moisture in the sample can distort the NIR spectra. Wrinkles influence the intensity of the peaks of the spectra, making the determination of the fibre share more difficult. Moisture changes the spectra, and with increasing moisture content, the water peak at 1390 nm dominates the spectrum.

Sorting on an industrial scale confirmed the observations made on a laboratory scale. Single-layer textiles were sorted into different categories of polyester with/without elastane, cotton with/without elastane, and polycotton of different ratios. The results show that NIR spectroscopy is suitable for sorting used textiles in an industrial environment. With some degree of uncertainty, textiles can be sorted into predefined categories. About 25 % of the sorted single-layer textiles are made of polyester or polyester blends.

Even though we have shown that the detection and NIR-based sorting of textiles is technically possible, there are still some challenges when it comes to textile sorting using NIR spectroscopy. First, a large database of textiles with known compositions and various blends to teach the sensor/software is needed. Second, the sorting categories have to be adapted to future recycling technologies. Third, coatings, additives, and dyes have not been investigated in this study but can have an influence on the spectrum. Fourth, multilayer textiles and core yarns, especially elastane, are still a challenge due to the penetration depth of NIR radiation.

The application of material sorting of textiles offers the possibility of determined input streams for future recycling processes. As shown in this paper, the usage of NIR spectroscopy is promising. Its implementation in the industry can be a major step towards a circular textile economy.

CRediT authorship contribution statement

Amrei Becker: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. Annika Datko: Writing – original draft, Investigation, Formal analysis, Data curation. Nils Kroell: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis. Bastian Küppers: Visualization, Validation, Supervision, Methodology, Investigation. Kathrin Greiff: Supervision. Thomas Gries: Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Amrei Becker reports equipment, drugs, or supplies was provided by Stadler Anlagenbau GmbH.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107577.

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