Influence of reflective materials, emitter intensity and foil thickness on the variability of near-infrared spectra of 2D plastic packaging materials

G. Koinig [a,*], K. Friedrich [a], B. Rutrecht [a], G. Oreski [b], C. Barretta [b], D. Vollprecht [a]

[a] Chair of Waste Processing Technology and Waste Management, Department of Environmental and Energy Process Engineering, Montanuniversitaet Leoben, Franz Josef Straße 18, Leoben 8700, Austria
[b] Polymer Competence Center Leoben GmbH, Roseggerstraße 12, Leoben 8700, Austria

ABSTRACT

Most two-dimensional plastic packaging materials are thermally recovered, which does not add to the recycling quota of 50 % required by EU legislation for all lightweight packaging until 2025. Furthermore, the separation processes for 2D materials cannot reach the same level of accuracy, which is possible in the sorting of rigid plastic packaging.

This study proposes new adaptations to existing sorting aggregates to increase the near-infrared spectral quality of two-dimensional materials. It aims to improve the spectral quality, which was defined by the deviation of the spectra from a reference spectrum and the variability of the recorded spectra, which can be achieved by installing reflectors behind the material made up of copper or aluminium. This setup enables detection in transflection rather than reflection mode.

The variability could be reduced by a factor of 6 through the use of a reflective background. Meanwhile, the spectral fidelity to the reference spectrum could be enhanced, in some cases decreasing the deviation from the reference spectrum by 30 %, which means enhancing a spectrum from unrecognisable to useable. Apart from using reflective materials, the effects of emitter intensity, material and thickness were evaluated.

1. Introduction

The material recycling of plastics requires substantial innovation in the next five years to achieve the environmental policy goals set by the EU. Including a recycling quota of 50 % for all lightweight packaging and an obligation for all lightweight plastic packaging material to be recyclable in a cost-efficient manner as stated in the Waste Framework Directive (2008/98/EC). For this reason, projects aim at identifying two-dimensional (2D) films in plastic sorting to increase the material recycling of packaging film waste. However, multilayer films are challenging to be mechanically recycled according to the current state of the art and negatively affect the quality of the other recycled plastics by polluting the recyclates if they enter the material stream.

Currently, mono- and multilayer packaging is recycled into low-value products as part of the downcycling process or are used as refuse-derived fuel (RDF) (Kaiser et al., 2018). This kind of treatment of flexible packaging is especially problematic since (co–)incineration does not reduce the CO_2 footprint to a degree like recycling would do.

Mono- and Multilayer sorting techniques are necessary to prepare collected lightweight plastic packaging material for further processing in recycling plants. According to Niaounakis (2020), the different technologies to recycle flexible packaging can be subdivided: Films can be collected in groups of identical materials or geometry either by manual or automated sorting systems. Workers and robots can pick and differentiate many polymers and geometries given a sufficiently low throughput rate of the material stream. Vacuum suction systems, air sifters and different screens, such as the vibrating screen or the ballistic separator, sort particles according to their respective geometries and free the material from contaminants.

Marking systems, like identification codes or fluorescent additives, enable material identification but are currently not adequate or economically feasible for widespread industrial application. These systems may change once further research increases their deployability soon (Woidasky et al., 2018).

Several chemical and physical experimental methods have been developed to separate multilayer films. Among these is the CreaSolve process developed by Fraunhofer IVV and the Creacycle GmbH. The CreaSolve process is a solvent-based operation that is theoretically capable of sorting post-industrial and post-consumer multilayer plastic packaging (MPP) (Frauenhofer IVV, 2021). So far, it has been implanted
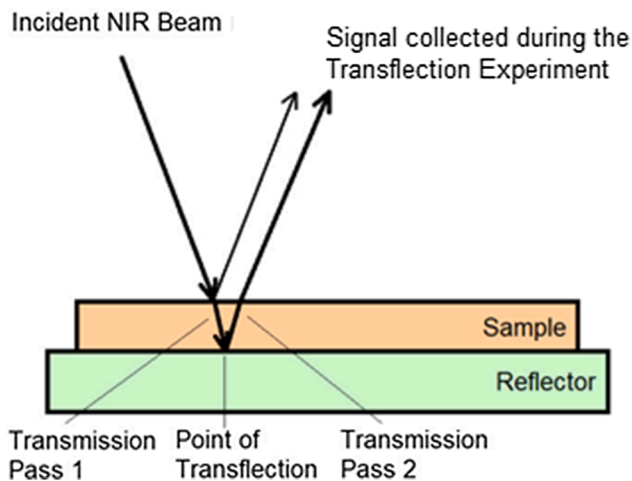
* Corresponding author.

Fig. 1. Scheme of the transflection measurement principle.

in one plant, separating only post-industrial waste to recover PE (Unilever, 2020). The common denominator amongst all industrial processes currently employed to recycle MPP is the need for a feedstock with specific and known material combinations (Chen et al., 2021). Currently, there is no solution to generate this kind of feedstock from post-consumer MPP to improve these MPP recycling processes. This lack is the difficulty of recognising post-consumer MPP in the sorting process because of the vast array of materials used in MPP (Chen et al., 2020; Niaounakis, 2020).

This paper aims to improve optical separation systems' capabilities to deliver this feedstock by improving MPP detectability in optical systems.

Optical systems stand out due to their ability to detect and eject various polymers at high throughput rates compared to other sorting methods, for example, manual sorting. Optical sorters use either visible (VIS) or near-infrared (NIR) spectroscopy or a combination thereof. However, they are sensitive to interfering influences and need specific material properties and controlled operating conditions to maximise efficiency (Burns and Ciurczak, 1992).

As there is no stand-alone solution to separate plastic into different polymer fractions, plant engineering uses established sorting technologies combined with optical or electrical systems to achieve the necessary output quality. The application of sorting cascades is standard in current lightweight packaging plants (Kaiser et al., 2018).

Though widely applicable, the sensor-based sorting technology is limited by various inherent problems in its operation principle. One is the need for sufficiently reflective material to gain necessary information for separation, which is often problematic with thin 2D materials.

Studies have shown the penetration depth of NIR radiation to be highly dependent on sample material and wavelength. Evaluations on NIR analysis of fruits have shown the penetration depth to vary from 2 – 3 mm in the spectral range of 900–1900 nm to 4 mm in the range of 700–900 nm (Lammertyn et al., 2000). Other studies examining the penetration depth of NIR in bone structures and cartilage have shown the penetration depth to vary between 6.3 and 8.5 mm and 0.5–5 mm, respectively depending on wavelength and material (Faris et al., 1991; Padalkar and Pleshko, 2015). This discrepancy between penetration depth and sample thickness can lead to problems when examining samples of 30 μm thickness or less in reflectance mode due to a loss of radiation to transmission and with that a loss of spectral information.

Preliminary analysis by Masoumi et al. (2012) has shown an increase in spectral information with growing material thickness. This effect is based on a rise in reflectivity. It leads to more pronounced spectra since differences in the spectral curve can be more easily identified with high reflectivity (Masoumi et al., 2012). This effect of reflectivity depending on material thickness can have detrimental impacts when measuring the

spectra of very thin 2D materials. This paper explores methods to gather valuable spectra even from very thin materials.

Though the recognition of thin plastic packaging is possible on a laboratory scale, very thin materials, especially PP with a thickness of 15–50 μm and PET with a thickness of 12–50 μm, were troublesome to identify because the materials were prone to the exhibition of sine wave spectra. These wave-like spectra complicated the identification of those materials (Chen et al., 2020).

This phenomenon of wave-like spectra in thin materials was studied by Jeszenszky et al. in 2004. It has been postulated that the wave-like spectra are caused by destructive interference due to the thin materials. This effect can lead to sine wave spectra, which are unusable for classification without further processing like fast Fourier transformation (Jeszenszky et al., 2004).

NIR sorting requires diffuse reflection for classification. If a material tends to direct reflection, the sorting becomes difficult or impossible. Rougher surfaces that tend to diffuse reflection are more accessible to separate than glossy and smooth surfaces prone to direct reflection (Küppers et al., 2019).

This paper explores possibilities to enhance the spectral information gathered from materials that tend to direct reflection, like PP foils.

Special attention in this paper is paid to the chute material and the illumination intensity. The thesis by Yu Xing Cui (2011), postulated that certain materials have particularly good NIR reflective properties. Likewise, preliminary experiments have shown the illumination intensity to have a positive influence on the sensor system. In this study, the hypothesis is tested whether and how both parameters influence the sorting result and whether one or both parameters are suitable for improving the spectra used to identify and separate packaging films.

The hypothesis tested in this study is which effect material thickness has on material identification via NIR spectroscopy. Further, this study aims to evaluate if there can be an optimum illumination setting for the identification of plastic packaging films and evaluate the influence of different reflective materials on the films' NIR spectra.

2. Materials and methods

A sensor-based sorting system serves as an experimental site to examine which adaptations can be made to the sorting set-up to facilitate the detection and separation of 2D materials. Therefore, in this paper, the technical limits of near-infrared sorting are investigated and explored. A novel measuring geometry is presented to shift these limits.

The sensor-based sorting aggregate used is an experimental NIR/VIS sorting setup provided by Binder + Co AG, representing the industrial standard. The material is manually applied over a vibrating chute with a width of 0.5 m, transporting it to the downstream sensors. The setup includes a NIR line scan sensor (EVK Helios – G2 – NIR 1), which was applied to record spectral images. NIR Sorting requires an infrared emitter.

For this purpose, an infrared lamp is utilised, which can supply 6.5 mW/mm^2 of light output in the detection area at 170 VDC, as measured with a Thorlabs S470C sensor. This sensor is sensitive to a wide range of wavelengths, making it suitable for measuring the intensity of NIR radiation.

The emitted radiation interacts with the particles and is reflected, transmitted, or absorbed depending on the material's molecular composition (Pasquini, 2003). If the measurements are taken in reflectance mode, only the dispersed reflected radiation can be detected by the NIR sensor and used for classification. The radiation is converted into a digital signal and stored in a hyperspectral imaging (HSI) cube with two spatial coordinates displaying the analysed area and a third coordinate representing the reflected intensity at each pixel (Manley, 2014; Reich, 2005).

In the utilisation of near-infrared technologies the measurement principles of transflection, reflection and transmission are distinguished. Fig. 1 shows the principle of transflection measurement schematically.

Table 1
Testing Material and the corresponding thickness.

Material	Thickness
Reference LDPE White	3 mm
Reference PP Purple	3 mm
PCW 55 – PE	20 μm
PCW 33 – PE	25 μm
PCW 56 – PE	50 μm
PCW 90 – PE	75 μm
PCW 45 – PP	30 μm
PCW 38 – PP	35 μm
PCW 41 – PP	45 μm
PCW 153 – PP	60 μm
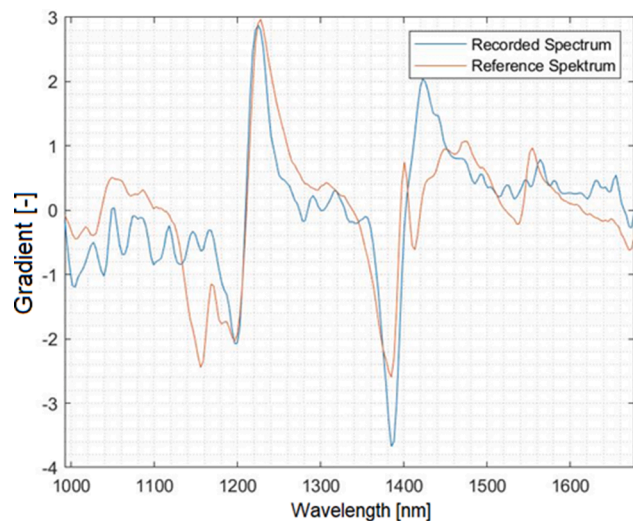
Fig. 2. Comparison between the PE reference spectrum (orange) and a PE foil spectrum (blue).
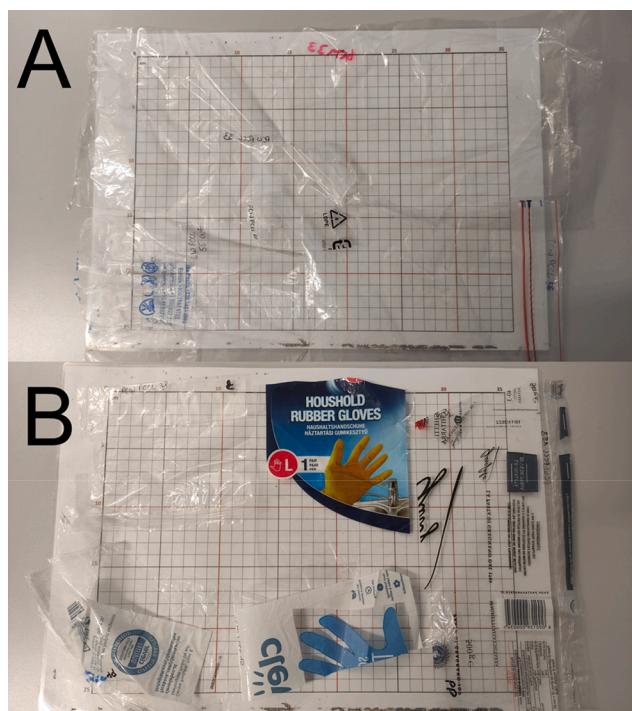
Fig. 3. Depiction of all Samples, A) PE B) PP.

First, an incident NIR beam is emitted to the sample, then the entrance angle changes and gets more acute for the transmission pass one. At the point of transflection on the reflector surface, the weakened NIR beam is reflected and passes through the sample at the transmission pass two with an acute reflection angle. Next, the reflection angle gets more obtuse at the sample surface, and this signal is sent to a computer, where the data is processed and analysed. Finally, the reflected signal and the transmitted signal at the sample surface before the transmission pass one are combined to a transflection signal. The transflection signal is analysed at the end of the experiment. The application of transflection increases the amount of information gained by the sensor since little to no radiation is lost to transmission. That is critical when applying near-infrared spectroscopy to thin materials. Measurements in transflection circumvent this problem.

The material consisted of two groups. Group A, the reference material, was specifically crafted to be used as a reference. This group consists of white LDPE and purple PP tiles, with a length of 5 cm, a width of 3 cm and a thickness of 3 mm. These materials were used to create a reference spectrum for later comparison to the 2D materials.

Group B consisted of the 2D foil materials to be evaluated. Eight samples of two different materials were selected. These samples were transparent to the human eye and showed varying thickness, as shown in Table 1.

Initial trials have shown that the spectra of group A and B are similar, barring minor differences attributable to the difference in thickness. Fig. 2 shows the comparison between the spectra of a PE reference material (orange) and the recorded spectra of a PE specimen (blue). Though the spectra show similarities in the minima and maxima at 1200 nm, 1230 nm and 1380 nm, a significant loss of information can be observed. This discrepancy between the reference spectrum is expected considering the difference in thickness.

Samples with varying thickness were chosen to evaluate the effect increasing material thickness has on the spectral images. Further, transparent samples were selected to eliminate the effect colourants have on the samples spectra and the image quality.

Fig. 3 shows all specimens selected for the evaluation. In (A), all PE samples can be seen, while in (B) all PP samples are shown. It can be seen that some areas of the samples were printed in order to advertise the products they contained. These areas were omitted during the analysis of the spectra.

Transparent sample objects were chosen to enable the comparison of the specimen's spectra, which enabled the comparison of thinner samples to thicker samples of the same material without the spectral changes different colourants would introduce. This way, the effect increasing thickness has on the spectra could be analysed. Since the material consists of authentic household waste, coloured sections occur in the specimen. However, these were excluded in the pixel selection for analysis to prevent colourants from interfering with the spectral analysis.

2.1. FTIR spectra of materials

In addition to the recycling marks present on most post-consumer packaging waste, FTIR spectra analysis of the foils was conducted in transmittance mode to create a reliable classification of the 2D materials. Thus, a material database was created, which served as the foundation for the following analysis on the experimental sensor-based sorting setup since knowledge of the materials composition was needed to choose the correct reference spectrum for comparison with the recorded NIR spectra.

2.2. Material preparation

Preliminary tests have shown that the effect of different reflective materials is more pronounced the closer the contact of material and reflector is. Therefore, to achieve maximum contact with the
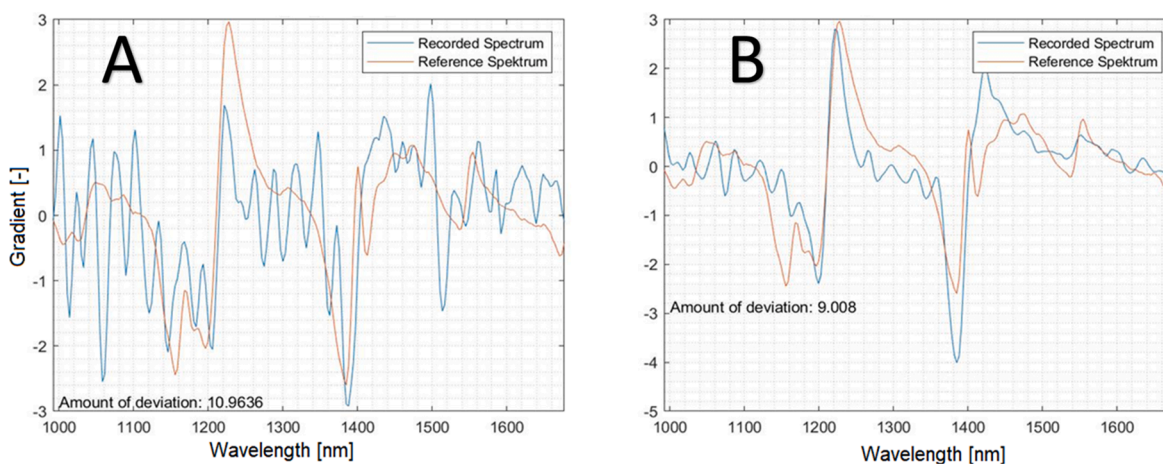
Fig. 4. Increasing fidelity to the PE reference spectrum of two spectral images taken without reflective background[A] and with a reflective copper background [B]

background and eliminate trajectory effects, each specimen was encased between two glass plates, one of which was covered with the respective background materials. This method ensured the same circumstances for every recording of spectral data. In addition, the known NIR inactivity of glass due to its high transmittance was tested during preliminary studies, which showed no substantial impact of the glass plates on the specimen's spectra.

2.3. Changes of emitter intensity

Preceding experiments have shown that increasing the emitter intensity has positive effects on spectral quality. Preliminary spectral examinations show the correlation of mean spectral quality with increasing emitter intensity. The spectral range from $1200 - 1400$ nm, which contains one of the typical PP spikes explained by Küppers et al. in 2019, becomes more pronounced with increasing intensity. The spectra at low-intensity lack discernible patterns useable for classification. Taking spectral images without sufficient illumination leads to random spectral intensity values. These random spectra lack any regularity and are therefore not suitable for classification. Preliminary evaluations to find the correct intensity range have shown that decreasing the emitter intensity increases spectral variability. Therefore, low emitter intensities are included in the trials, reducing the emitter intensity to further evaluate the effect of low NIR intensity on spectral quality.

However, it is not necessarily the case that maximum emitter intensity is always beneficial since a change in background material causes a change in reflectivity. Furthermore, because only dispersed reflections can be used for classification, increasing the emitter intensity excessively can lead to direct reflections and overexposure, which render the affected pixels and their spectra unusable. Therefore, every reflector material was evaluated using the emitter intensities 70 %, 80 %, 90 % and 100 % of the maximum intensity, or 4.55 mW/mm^2, 5.20 mW/mm^2, 5.85 mW/mm^2, 6.50 mW/mm^2 of light output in the detection area respectively, to analyse the effect changing intensity has on the spectral quality.

Background Material

Gold, copper, silver, glass, aluminium and a black polymer, coloured with carbon, were considered as background materials due to their optical properties in the relevant wavelengths. All materials, except black polymer, chosen as the negative benchmark, are promising to be usable as a reflector because of their high reflectivity in the near-infrared wavebands. The black polymer was chosen as a background to present a negative benchmark to which the metal backgrounds could be compared. Coincidentally, the black polymer reflector represents the common conveyor belts used in most sorting aggregates whose top covers are usually made of black polymers. The respective reflectance of

the materials is shown in Fig. 7. These reflectance values were taken via FTIR spectroscopy.

The materials used as background were a copper plate with 99.9 % copper content, black PP polymer and rolled 100 % aluminium. The reflector materials were applied to the sample holder behind the respective sample.

2.4. Data evaluation

A Matlab R2021a script was used to extract the spectra from the Hyper Spectral Imaging Cube to gauge the quality of the spectral images taken of the materials.

This Matlab script enables the user to choose viable pixels for evaluation. It then computes the normalised first derivative of the spectra and presents a smoothed graph of the data points, using a Gaussian smoothing algorithm with a 10-datapoint interval. The image quality is defined as the variability of the spectra in its spectral range for a specific material. For this reason, the variability was computed by calculating the difference between the area integral using trapezoidal numerical integration of the spectra with the maximum intensity and the spectrum with minimum intensity.

The sensor measures the spectral intensity in Arbitrary Light Units (ALU), which is a unit used by the sensor provider EVK, and the spectral wavelength is measured in nanometres; the integration of the first derivative also yields the area in ALU. The y-axis is denominated as ALU/nm since it is the gradient of the raw spectrum.

This calculated area between the spectrum with the lowest intensity and the spectrum with the highest intensity indicates the variability, suggesting the spectral image's viability. Since the image's quality depends on the parameters under which the image was recorded, a small area between the two spectra indicates a recording of high fidelity with beneficial parameters.

Because not all wavebands are equally crucial for the classification, this computation was limited to those, which hold relevant spectral data for classification. Those wavebands were selected by evaluating the first derivative of the raw spectral intensity data. Wavelengths, in which the first derivative deviates substantially from zero, indicate the interaction of the material's molecules with the NIR radiation. This interaction results in a unique spectrum that can be used to classify the given material. This classification is the basis for separation using pressurised air.

Since a spectrum can exhibit low variability but still deviate from the benchmark spectra, rendering it unfit for classification, a second spectra quality criterion was needed. For this purpose, the deviation of the mean spectra from the benchmark was used. Initial trials showed that recorded spectra increasingly approached the reference spectrum with increasing background reflectivity. This effect is depicted in Fig. 4, which shows the
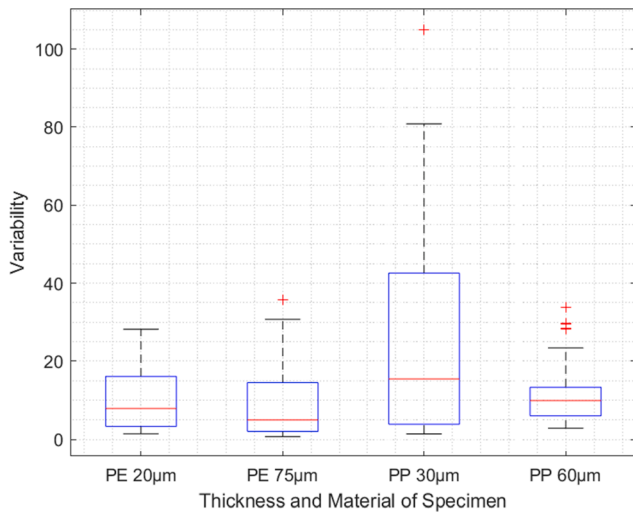
Fig. 5. Influence of spectral variability depending on thickness and material.
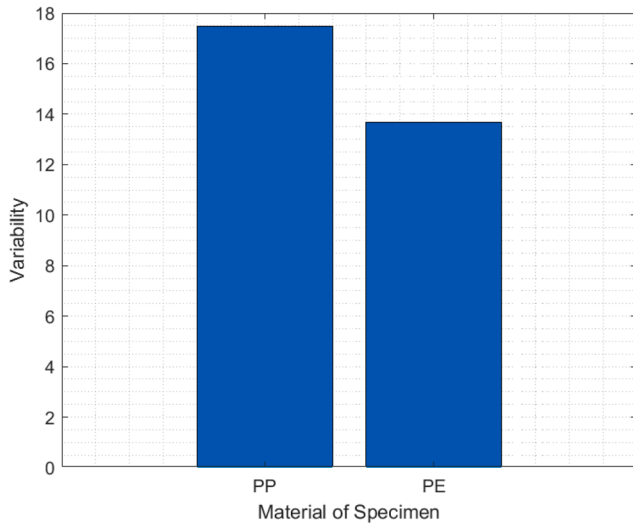

Fig. 6. Difference in average variability depending on specimen material.

increasing fidelity of the recorded PE spectrum to the PE reference spectrum. It can be seen that the spectra recorded without a reflective background (A) do not follow the reference spectrum as well as the spectra recorded with a reflective copper background (B) do. The amount of deviation shown in the figure is the sum of the differences between the recorded spectrum and the reference spectrum.

This difference, or deviation, is calculated with the Euclidian (2-norm) by subtracting the mean spectra of the selected pixels from the benchmark spectra. This calculation yields a numeric value that indicates the deviation of the HSI spectra from the benchmark spectrum, with low values indicating high fidelity to the benchmark spectrum. With that, an estimation of the usability for the classification of the material can be made.

Normalisation was applied to every spectrum using the 'z-score' method to enable the comparison. The 'z-score' method centres and scales the data to have a mean zero and standard deviation one.

$$Zscore(e_i) = e_i - \frac{\overline{E}}{std(E)}$$

$$std(E) = \sqrt[2]{\frac{1}{n-1} * \sum_{i=1}^{n} (e_i - \overline{E})^2}$$

$$\overline{E} = \frac{1}{n} * \sum_{i=1}^{n} e_i$$

Equation 1: Calculation of Z-Score Normalization

To create spectra for evaluation each recording was repeated five times. For each of those recording, nine pixels for spectral evaluation were selected. Here, care was taken to avoid overexposed pixels and pixels on the edge of the material and coloured portions of the material. This approach yields 45 suitable pixels per setting for evaluation.

In order to evaluate whether a relevant correlation between the examined experimental variables and the spectral quality exists, regression curves were fitted to the experimental data. The goodness of fit of those regression curves was evaluated by calculating the coefficient of determination (R^2) for each fit.

3. Results and discussion

The first results are the decrease of variability and deviation with the increase in material thickness, which was further examined based on the assumption that the increase in spectral quality is different for the chosen materials. Subsequently, the effect the reflecting backgrounds and increased illumination intensity had on the variability was
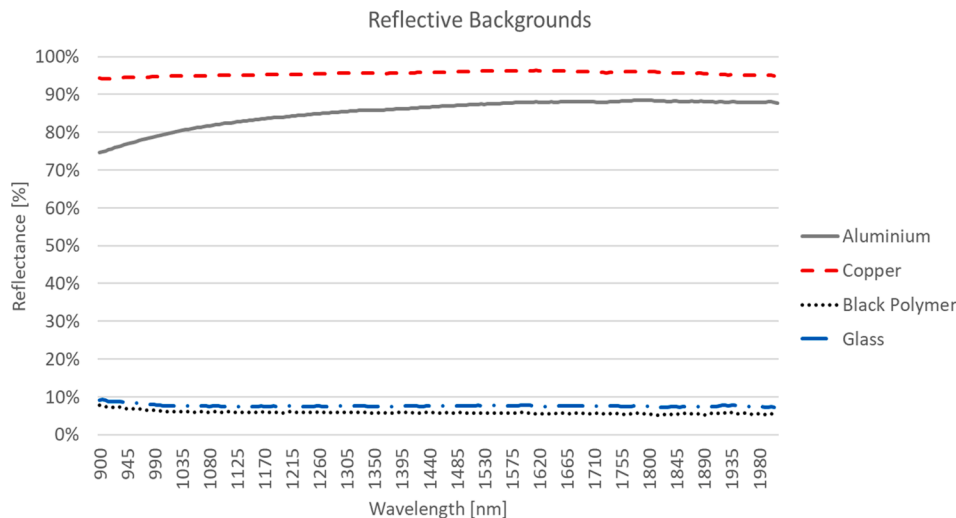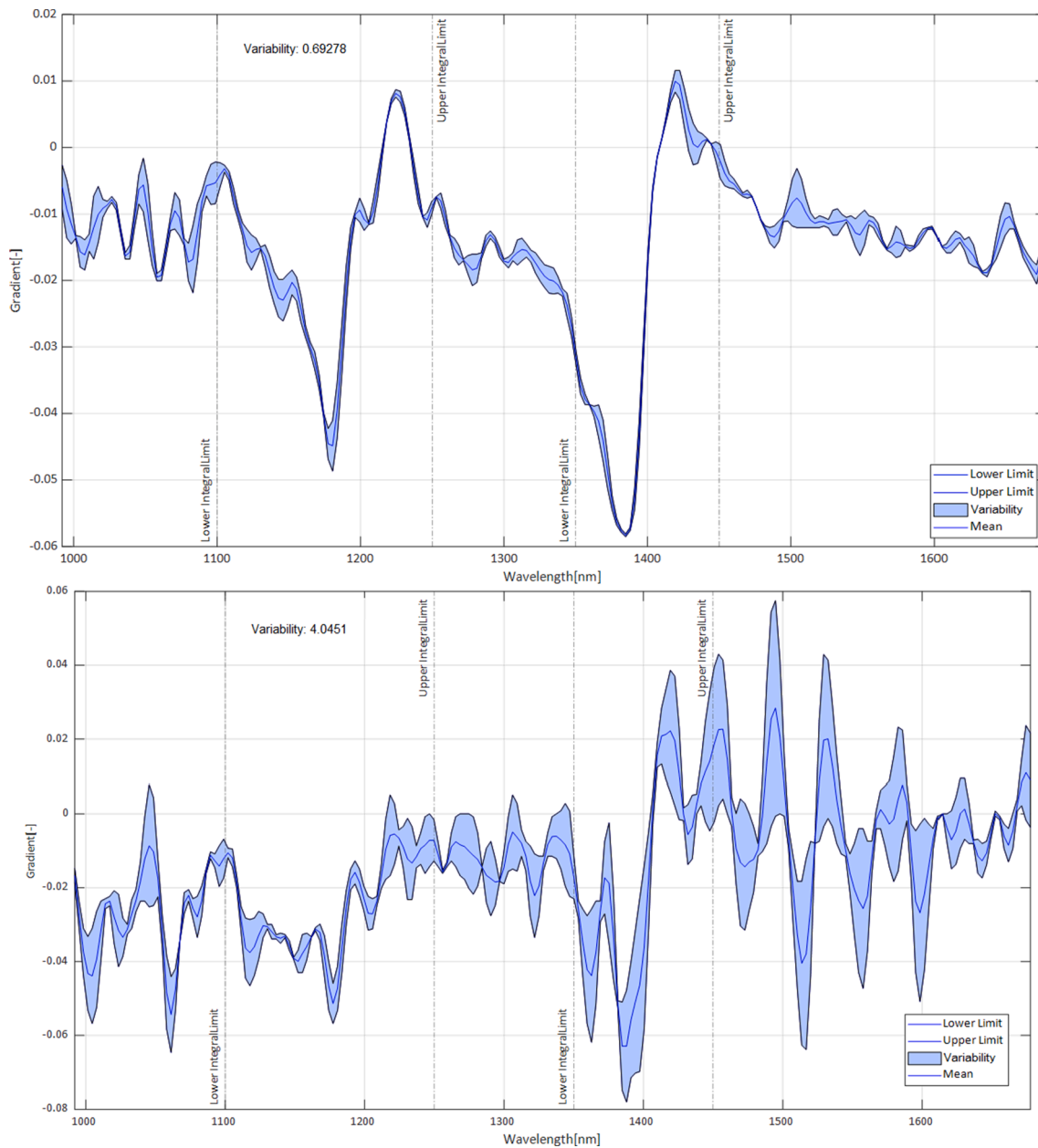

Fig. 7. Reflectance of chosen reflector materials.

Fig. 8. Reduction in spectral variability due to increased reflectivity of background material and subsequent measurement in transflection. A) No reflector B) Copper reflector.

quantified.

3.1. Influence of thickness

With 2D materials, a rise in material thickness decreased spectral variability. The intensity of this effect is correlated to the material used. While PE spectra exhibited comparatively low variability even in specimens with low thickness and had limited room for improvement, PP spectra reacted strongly to the increased material thickness with improved spectral quality.

Fig. 5 shows a box and whisker chart displaying the comparatively high variability of PP spectra compared to PE spectra. While increasing the thickness of PE specimens lead to a small decrease in variability, increasing the thickness of PP specimens lead to a more pronounced decrease in variability.

Examination of PP materials with a thickness of under 35 μm yielded spectra in sine waveform. So far, these cannot be used for classification

since the occurrence of sine wave spectra is currently not precisely attributed to a specific chemical or physical property of a specific resin. It is related to the thickness of a foil and occurs below a certain threshold thickness. This thickness is material-specific. However, it has been postulated that the sine wave effect occurs because of destructive interferences if a given correlation of the material thickness and wavelength is present. These interferences can be removed by applying fast Fourier transformation (Jeszenszky et al., 2004). It can further be confirmed that this phenomenon occurs below a certain thickness and the novel information that the threshold thickness is between 30 and 60 μm for PP can be added.

3.2. Influence of material

The PE specimen showed on average spectra with less variability, even in specimen with low thickness, while PP materials produced spectra with high variability. With PP expressing on average 28 % more
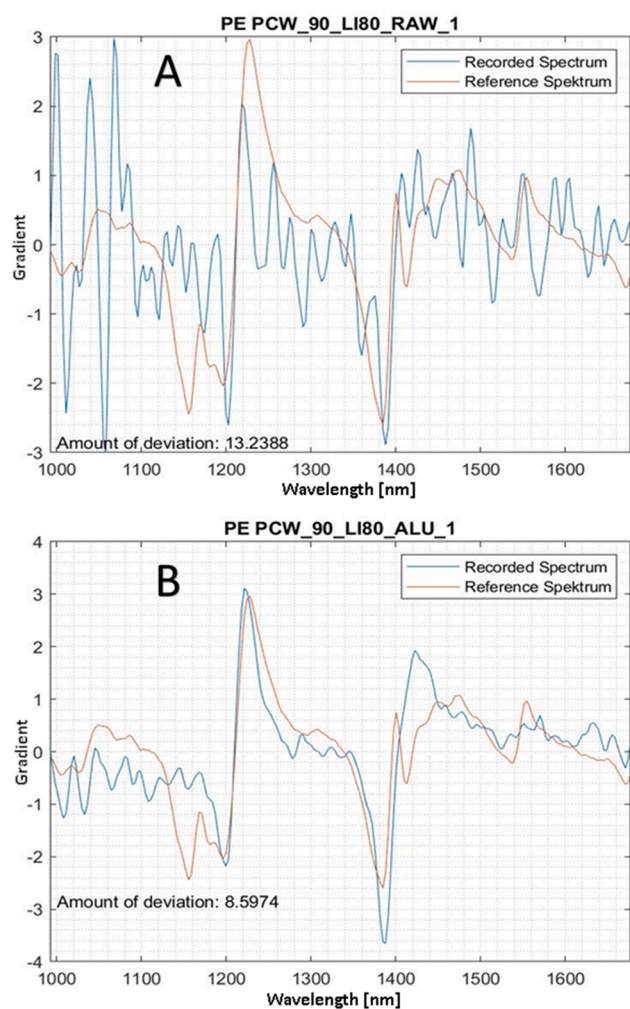
Fig. 9. Reduction in spectral deviation from the reference spectrum due to the effect of reflector material, A) No reflector B) Aluminium reflector.

variability from the mean spectrum. It can be seen in Fig. 6 that the PP specimens exhibit overall higher variability than the PE specimens.

PE yielded more useable recordings due to the higher reflectivity of the PP materials, which leads to more direct reflection instead of the useable diffuse reflection. This direct reflection yields overexposed pixels, which cannot be used for spectral analysis. Overexposed pixels cannot be used for classification due to the detectoŕs inherent limitation to processing very bright pixels. This limitation is handled by capping the maximum intensity value. If the intensity of a pixel exceeds this limit, it is simply reduced to this pre-set value. If all spectral values of this pixel are set to this value, the spectrum contains neither maxima nor minima and is a straight line instead. So, no further evaluation by derivation or other forms of processing can yield any valuable information for classification other than classifying this pixel as overexposed.

Since NIR detection uses the interaction of radiation and the material for classification, the molecular composition and material thickness heavily influence the detection outcome. This effect is especially pronounced when analysing thin materials like monolayer packaging, which routinely exhibit material thickness under 100 μm. While they yield similar spectra, due to resemblances in their chemical makeup, PE and PP, two common materials for monolayer packaging, exhibit differences in spectral quality when used for spectral analysis. These differences become increasingly pronounced with decreasing material thickness.

3.3. Influence of reflector and reflectance

Spectral images were recorded with different reflector materials behind the 2D specimen to facilitate the interaction of the 2D foils with the NIR radiation. This approach yielded improved spectral with decreased variability. This effect depended on the reflectivity of the given background material in the relevant wavebands from 900 nm to 2000 nm. Fig. 7 shows the reflectivity values of the various backgrounds as taken in FTIR spectroscopy.

Backgrounds with little to no reflectivity, e.g., black polymers or glass, had no improving effect on the recorded spectra. Increasing the reflectivity of the background material decreased their variability and enhanced the spectra's fidelity to the reference spectrum, as shown in Figs. 4 and 5, respectively. While aluminium showed promising results in preliminary examinations when virgin aluminium foils were used, the increasing formation of an aluminium oxide layer on the reflector's surface impaired its reflectivity, reducing the possible improvement of spectra recorded with this particular reflector. This reduction in reflectivity compared to virgin aluminium is shown in Fig. 7. Copper reaches approximately 10–20 % higher reflectivity than aluminium. Copper lends itself to the application as a reflector since it reaches the highest reflectivity of any material evaluated. Although not encountered during this study, the formation of copper verdigris on the reflector may become an issue.

The data analysis shows that spectral variability could be reduced by the use of copper and aluminium reflectors. This reduction renders a spectral image useable for classification since the pixel of the image deliver similar spectra. However, spectral analysis relies on creating a reference spectrum from the average of multiple pixels' spectra to determine to which material class a specific specimen belongs. Therefore, high variability of spectral information due to optical effects and imperfect reflection of near-infrared radiation in the images renders them unfit for classification.

It was shown that spectral images of 2D materials taken without a reflector exhibit a wide variation in the spectra extracted from viable pixels. Meanwhile, spectral images recorded using a reflector minimise the variability in the respective image. This reduction in variability around the mean, especially in the spectral ranges relevant for classification, is depicted in Fig. 8, showing the same material recorded under identical NIR intensity. In addition, the variability is reduced by a factor of 6 by using a reflective background.

Further, the spectral fidelity to the reference spectrum could be enhanced, in some cases decreasing the deviation from the reference spectrum from 13 to 8.5. This decrease in deviation from the reference spectrum entails that the spectrum of the specimen matches the reference spectrum more closely with increasing background reflectivity.

This increased fidelity to the reference spectrum combined with decreased variability means enhancing a spectrum from unrecognisable to useable. This reduction in deviation heeds from eliminating unwanted optical interferences and increased near-infrared intensity through transflection.

This elimination of optical interferences facilitates detecting the materials' inherent spectra, which lends itself to usage in separation processes. The comparison between the two spectra is depicted in Fig. 9, which shows the mean spectra of evaluated pixels in an image taken without a reflector compared to an image taken with an aluminium reflector of a PE film material.

3.4. Influence of emitter intensity

While increasing the emitter intensity did not change the deviation, increasing the intensity decreased spectral variability from 16.78 at 70 % emitter intensity to 13.68 at 100 % intensity. Although interesting, the effect increased intensity has is minuscule compared to the improvement obtained by increasing the reflectivity of the background. It has to be noted that an increase in intensity is comparable easy to
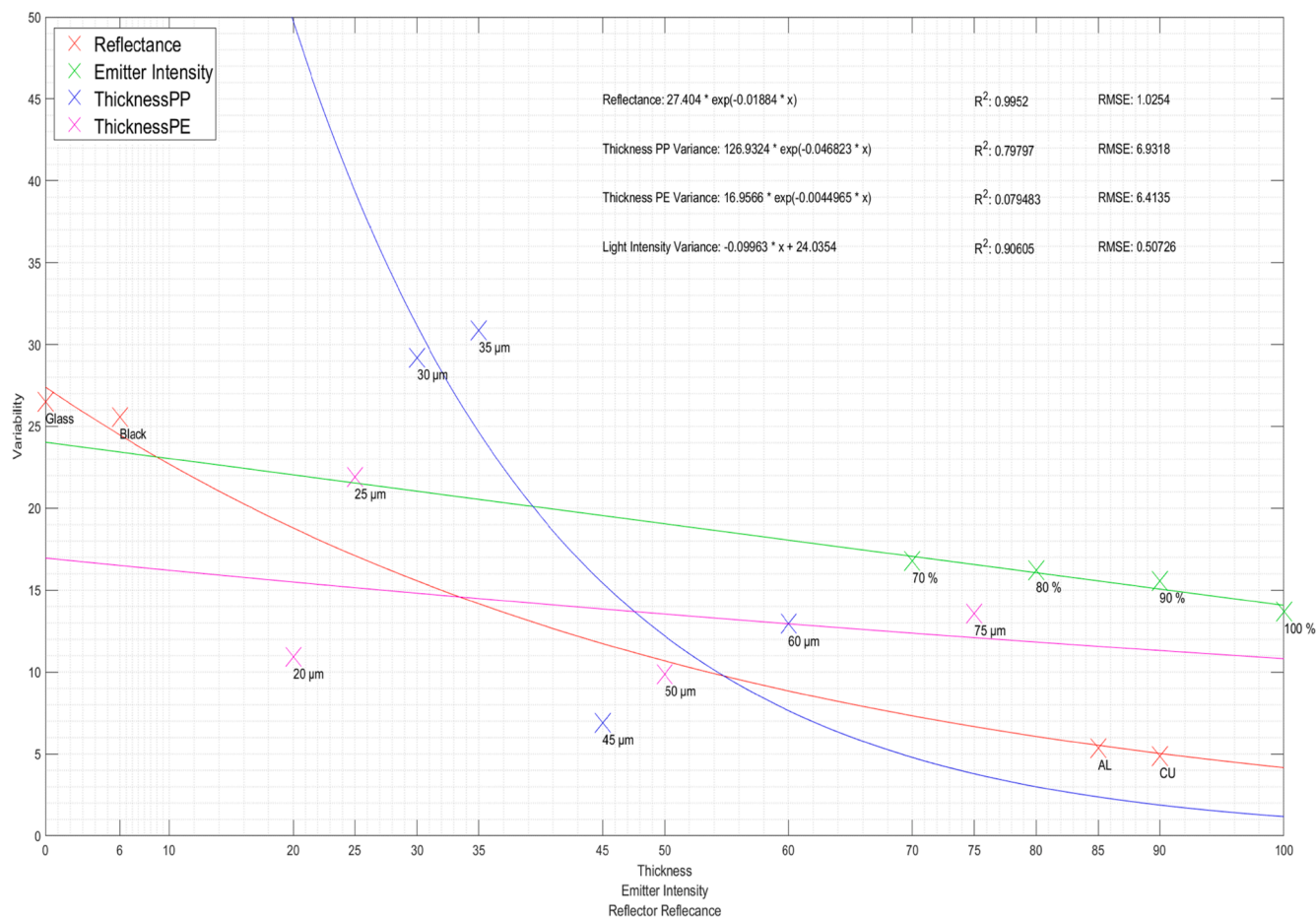
Fig. 10. Statistical evaluation of the effect changing various parameters has on the spectral variability.

achieve, needing no further adaptions to the sorting setup other than to increase the emitter intensity in the given control software. The increase in spectral quality heeds from the simple effect increasing the intensity has on the sensor-based sorting setup. With increasing intensity of the incident NIR radiation, more useful disperse reflection can occur, which is then detected by the near-infrared sensor for evaluation. This simple principle can improve the sorting result in recycling plants with relative ease if the hardware permits changing emitter intensity.

3.5. Discussion of statistical relevance of correlations

Fig. 10 shows the summary of the spectral evaluations and the effects the parameters had on the variability of spectral recordings. It shows the effects of different changes in the experimental setup on the spectral variability. Further, the regression curves for the evaluated data with their goodness of fit values R^2 and the root mean squared error (RMSE) are displayed.

The data points shown in the figure correlate to the average variability of the spectra and the given experimental settings.

It can be seen that no correlation between increasing thickness of the PE specimen and the spectral variability could be established. The PE specimen started with relatively low variability, even with a thickness of 20 μm and the variability did not decrease with increasing thickness. This lack of correlation is further supported by the R^2 value of 0.08 of the fit, which indicates that over 90 % of the variation is unexplained by the model.

Increasing thickness of the PP specimen showed a decrease in spectral variability during the study. It can further be seen in the regression curve for the PP specimen, which shows an R^2 value of 0.79. The PP specimen had an inherently higher variability and improved noticeably

when material thickness increased. This effect is also caused by the decrease of sine wave spectra encountered with thicker specimens.

A rise in emitter intensity showed a slight decrease in spectral variability, improving the spectral recordings, which is supported by the regression curve. Though not as noticeable an effect as the increase in thickness, raising the emitter intensity improved all spectral recordings. The regression shows an R^2 value of 0.91, which indicates a good fit for the given data.

During the trials, increasing the background material's reflectance showed the most significant influence on spectral quality, with aluminium showing promising results and the more reflective copper reflector improving the spectral recordings further. This effect showed to improve the spectral quality of all specimens, regardless of thickness or material type. Further, this effect is supported by the regression curve for the spectral variability and the reflectivity of the respective background yielding an R2 value of 0.99.

Increasing the reflectivity of the background material to enable measurement in transflection yielded the best results for improving spectral quality.

4. Conclusions

The key findings of these trials were the effects reflective backgrounds have on the spectral quality of plastic films with a thickness of under 100 μm, which are mainly used in the packaging of goods. The spectral variability decreased substantially when using a reflector made of copper or aluminium as background. Implementing a reflective background enables the measurement to be taken in transflection rather than sole reflection, which circumvents the problematic low reflectivity of thin-film materials. While introducing a reflector decreased

variability and deviation from the reference spectra in PE and PP materials, spectra of the latter showed more significant improvements as PP spectra displayed lower spectral quality without changes in the measuring geometry.

Apart from reflectors, increasing the emitter intensity in a sensor-based sorting rig increased spectral quality and fidelity to a reference spectrum. This method seems to be a convenient way of improving the sorting success of a lightweight packaging sorting operation by simply adapting the existing hardware to 2D materials by increasing the intensity setting for the near infra-red emitters. Presupposed the specific machinery design permits this technical modification and all safety concerns are addressed.

Coherent with existing findings, an increase in thickness improves the spectral quality of both PE and PP specimens, with PP showing more considerable improvements with increasing thickness, partly due to the sine wave phenomenon occurring less frequently with increasing material thickness. However, increasing the thickness of packaging is not the solution to the increasing demand for recyclable 2D packaging since the comparative lightness of these packaging materials renders them competitive.

A way to increase the recycling quota of 2D materials is to adapt existing sorting setups to use measurements in transflection, whose viability was shown in this examination, to improve the mechanical recycling of 2D materials.

Further studies are needed to examine the effect reflective backgrounds have on the sorting success of 2D materials on an existing sorting rig with the adaption of reflective backgrounds made of copper or aluminium, which have shown the most significant potential for use as reflective backgrounds.

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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.

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