06/2024

White Paper

PLASTIC SORTING WITH HYPERSPECTRAL IMAGING

This white paper explores the use of hyperspectral imaging for efficient plastic sorting, featuring two cameras from HAIP Solutions: the BlackIndustry SWIR 1.7 Max and the BlackIndustry NIR. They cover the wavelength ranges of 900-1750 nm (SWIR) and 700-1050 nm (NIR). Examples of sorting plastic flakes and plastic plates will be presented, demonstrating the technology's precision and versatility.

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Content

HAIP

Plastic Sorting with HSI

Nowadays, plastics are used in great variety and quantity in almost all economic sectors. A large proportion of the plastics used are produced from fossil oil and later accumulated as waste. The aim should be to increase the proportion of reused plastics (recyclates) as much as possible to create a circular economy. In order to be able to use plastic waste as recyclate, it is necessary to sort the different types of plastic and separate them from foreign materials. To make this process efficient and economical, it must be highly automated, which requires optoelectronic systems to detect the different types of plastic. Hyperspectral cameras have proven to be suitable for this purpose and have established themselves in practice. This white paper aims to provide valuable information on how the identification and sorting of plastics is carried out using hyperspectral technology. It can be further expanded in the future to significantly increase the proportion of material recycling, as with other materials like for example paper and wood.

1. Plastic Recycling - Status Quo

A large proportion of the waste generated by humans is plastic. In 2020, the global plastic production amounted to around 450 million tons (European Environment Agency, 2023). In Europe, the plastic production reaches up to 57.2 millions tons in 2021 (European Environment Agency, 2023), whereas Germany's amount of plastic waste sums up to 5.67 millions tons in the same year (Umwelt Bundesamt, 2023). A relevant problem concerning the correct recycling of plastic products is the difficulty to separate mixed plastic waste by polymer type. There is a large variety of plastic types and additives, altogether about 10,000 chemical substances like base materials (monomers) and additives being used in global plastic production (Science Media Center Germany, 2022). Poor sorting therefore results in mixed recyclates of lower quality. In order to avoid this problem and make plastic recycling as efficient and exact as possible, the development of new technologies and the refinement of already exsisting ones into economical products is a neccessary requirement.

The number of sorting machines used for recycling is constantly increasing. Their function is sorting the waste into its material fractions using multispectral or hyperspectral camera systems. Hyperspectral systems are becoming increasingly widespread, as this technology currently achieves the best sorting results at high throughput rates. They capture detailed spectral information across a wide wavelength range, allowing for precise identification and differentiation of materials. This high level of spectral and spatial resolution, combined with rapid data processing capabilities, results in superior sorting accuracy and efficiency at high throughput rates. However, the following limitations have delayed the faster spread of this technology among machine builders of plastics recycling machines worldwide:

- Very **complex** integration of hyperspectral technology with hardware and software, since there are no standardized complete solutions available
- HSI cameras were **slow** and had a **low resolution**: long return of investment period (low throughput rates of the machines)
- **Expensive** HSI camera technology
- Black plastics can only be sorted with an expensive MWIR technology

Today, these restrictive requirements have been largely overcome and new possibilities have opened up.

The most important criteria are:

- Affordable device price with larger quantities
- Low light requirement (with short exposure times)
- High frame rate; corresponds to high resolution in the direction of movement of the items to be sorted
- High local resolution of up to 1280 px
- Very good signal-to-noise ratio for stable detection of thin objects (e.g. foils)
- Extended wavelength range including a third absorption band of plastics

This white paper provides all relevant information for the use of hyperspectral technology on sorting machines for plastics processing as well as criteria for the selection of the various system components.

2. Scientific Basics

Hyperspectral Imagery is based on the spectroscopic analysis of the chemical components of objects, such as plastics. The absorption of electromagnetic radiation, especially infrared, triggers the vibrational activity of molecules. The resulting characteristic vibration bands or absorption bands of the respective molecules can be recorded by a hyperspectral camera (Figure 1). This is generally possible in the spectral ranges of the NIR, SWIR and MWIR. The most important criterion for the identification of different plastics is consequently the selection of a suitable HSI system.

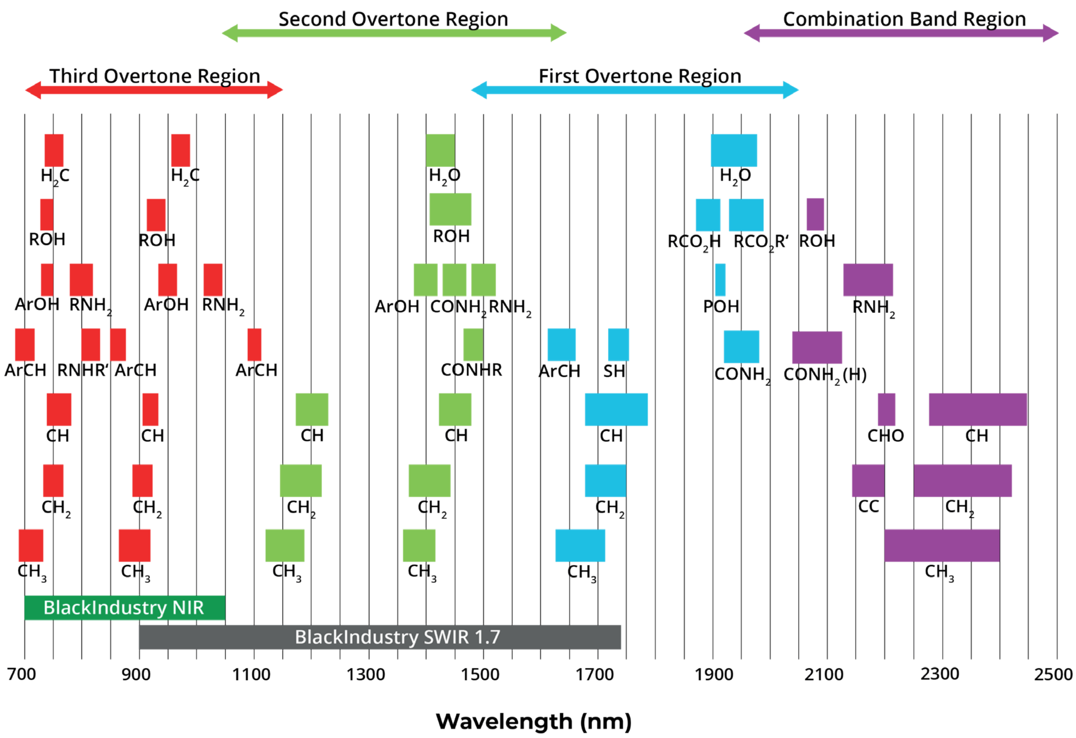


Figure 1: Absorption bands of important molecules

Systems that cover the SWIR spectral range (900 nm – 1750 nm) with InGaAs sensors are widely used in practical applications, followed by VIS/NIR systems (400 nm – 1050 nm) with CMOS sensors (Fig. 2). The MWIR spectral range (2900 nm - 4200 nm) is used for sorting black plastics, but it will not further be discussed in this white paper. There has been significant progress in CMOS and InGaAs sensor technology in recent years (SenSWIR, Nyxel and STARVIS2 technology). As a result, camera systems have also been further developed, opening up new application fields.

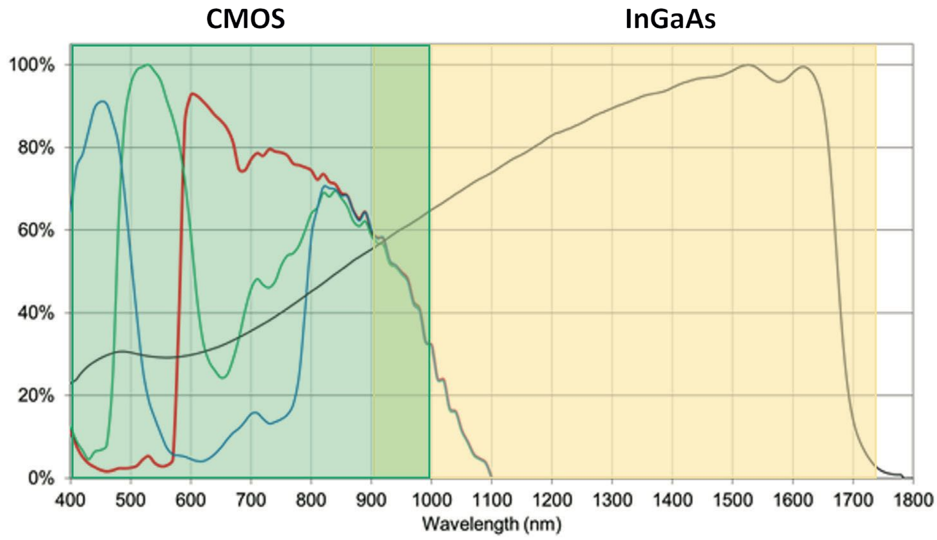


Figure 2: Sensitivity of CMOS and InGaAs camera sensors

3. Structure of the Investigation

This white paper aims to provide valuable information about the identification and sorting of plastics using hyperspectral technology. Based on the new sensor technologies CMOS and InGaAs, two hyperspectral cameras from HAIP Solutions are presented in this report:

- The CMOS-based hyperspectral NIR camera **BlackIndustry NIR** (700 – 1050 nm)
- The InGaAs-based hyperspectral SWIR camera **BlackIndustry SWIR 1.7 Max** (900 – 1750 nm)

Two applications are considered:

- The generation of reference spectra of typical plastic types
- The investigation of industrial plastic flakes made of PET and PE

Figure 3: BlackIndustry SWIR 1.7 / Max (left) and BlackIndustry NIR (right)

Feature	BlackIndustry NIR	BlackIndustry SWIR 1.7 Max
Wavelength range in nm	700 - 1050	900 - 1750
Spectral bands	89	Up to 420
Framerate Full Frame in Hz	540	210
Framerate ROI	Up to 1000 Hz	Up to 1330 Hz
Spatial Resolution	1920 pixel	1280 pixel

The first section introduces the mounting arrangement within the sorting machines and the illumination technology. Afterwards, both use cases are examined with both camera systems, first with the BlackIndustry SWIR 1.7 Max and then with the BlackIndustry NIR. The results are then compared before final suggestions are provided.

4. Mounting Arrangement

The location of the hyperspectral camera in the sorting machines is decisive. It is common to implement object detection either on conveyor belts (mainly coarse fractions) or on chute systems (mainly flake sorting).

There are two different mounting arrangements: Reflection arrangement and transflection arrangement. The reflection arrangement is defined as the recording of the light reflected by the object. This is due to the black conveyor belts, installed in the sorting machine. With colored belt systems, the reflected light from the belt can also be used, but the objects must be classified in such a way that the spectral properties of the belt are eliminated, especially in the case of transparent materials. A light-colored background can be selected for chute or free-fall systems (ceramic tile surfaces or Teflon have proven to be effective). This allows the objects to be measured in a transflective arrangement, making a significant difference in detection, especially for transparent objects. A typical machine setup consists of the following elements:

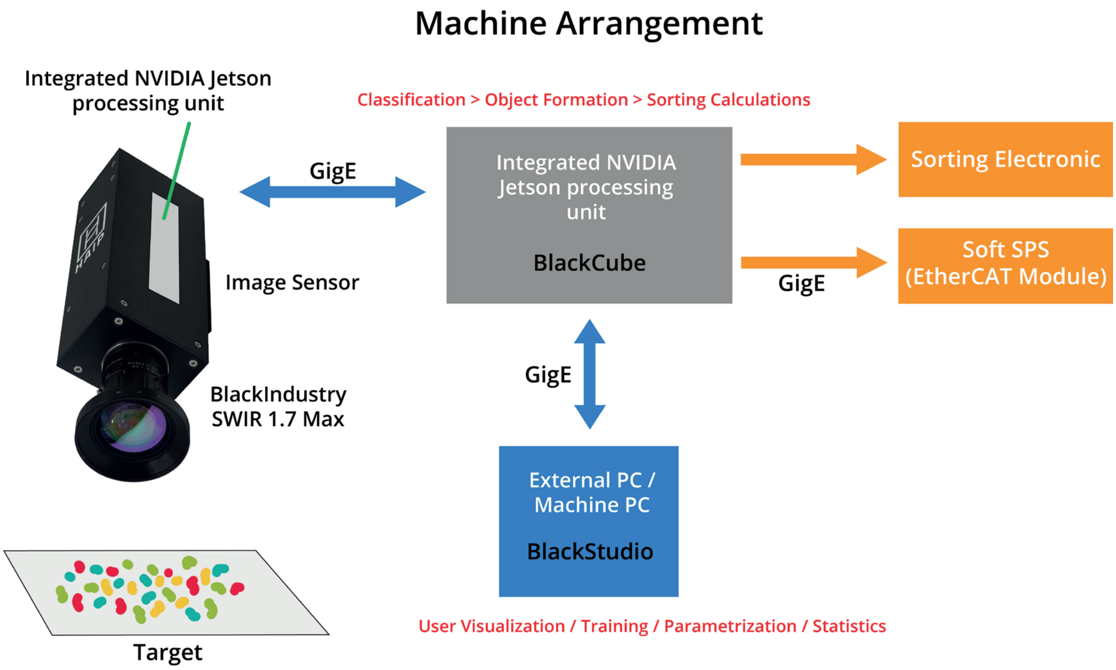


Figure 3: Typical configuration in a machine for plastic sorting

5. Illumination

In the SWIR technology, illumination systems with halogen emitters have prevailed. Halogen lighting is very suitable in many aspects but has some disadvantages. This includes the limited lifetime of the light sources, the high heat input at the measuring point, the high energy requirement and, in some cases, the problem of splinter protection, for example in food technology. The latest alternative to halogen illumination are the fast medium wave IR emitters. With their peak response being 1500nm, and the halogen peak response being at only 1100 nm, the fast medium wave IR emitters cover the spectral range of the SWIR in a more efficient way in terms of intensity distribution and power consumption. This is especially important for the third absorption band of plastics. In the field of VIS/NIR systems, halogen lighting is also typically used as standard. By now, LED technology has been developed to such a degree that the BlackIndustry NIR camera can be operated with a broadband LED illumination bar, the BlackBright VNIR LED Bar (Fig. 4).

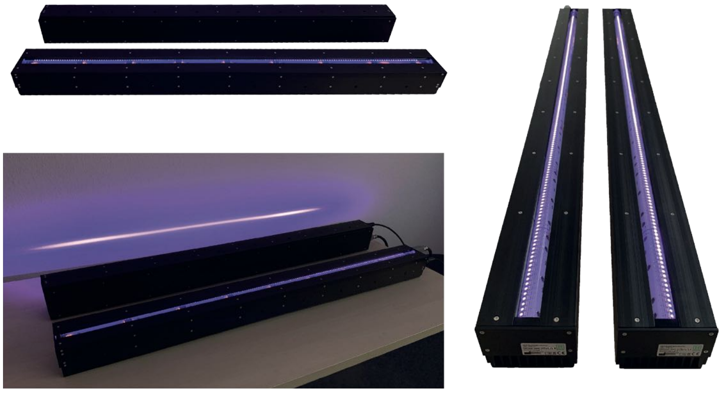


Figure 4: LED Illumination for BlackIndustry NIR

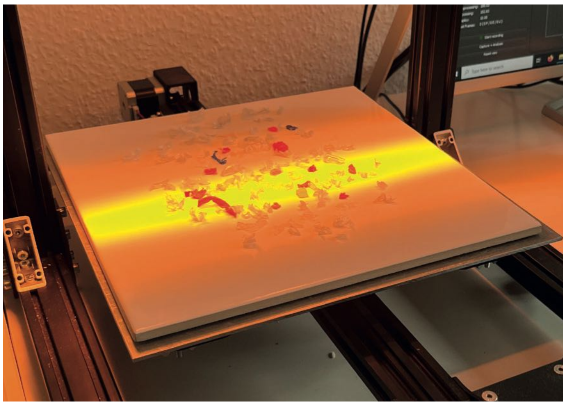


Figure 5: Fast Medium Wave IR Illumination

6. Application Setup

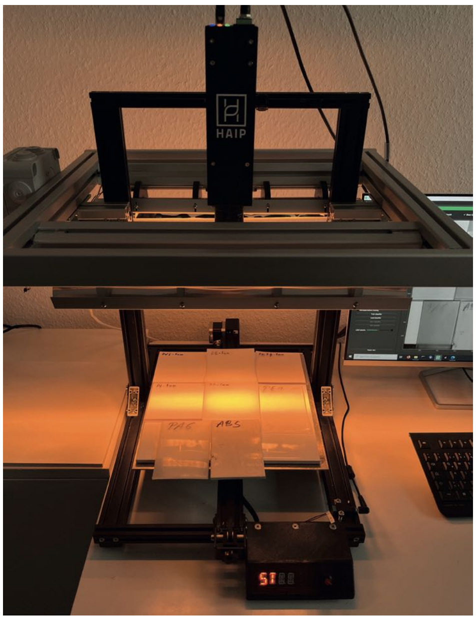


Figure 6: Test setup with BlackIndustry SWIR 1.7 Max

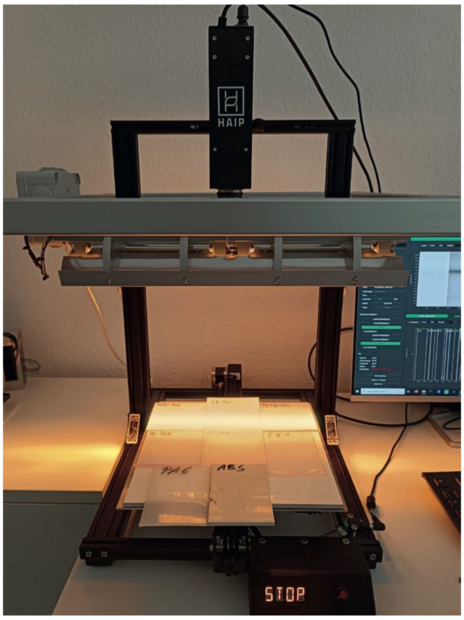


Figure 7: Test setup with BlackIndustry NIR

6.1 Reference Samples – Plastics

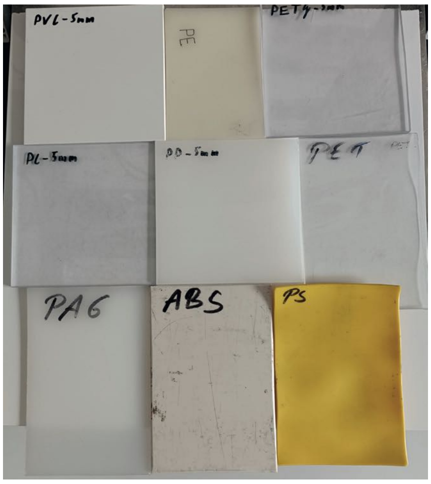


Figure 8: Photo of reference samples

A reference data set was created for the typical plastics PE and PP (polyolifins), ABS and PS (styrenes), PVC, PA6 and the transparent plastics PET, PETG and PC. This selection is characteristic of the most important plastics to be recognized in the recycling industry. The reference plates are light-colored or transparent and were recorded on a moving test setup with optimized Fast Medium Wave IR illumination. The hyperspectral images were aquired and analyzed using the BlackStudio software. The classification of the data with the BlackStudio software was carried out using the **LDA method**.

6.2 Scenario - Plastic Flakes

Mixed colored and transparent plastic flakes are used to illustrate a real application scenario. The adjacent figure shows a typical image of these plastic flakes, which were obtained directly from a shredding machine. They are transparent PET flakes and colored PE flakes, which are particularly common in PET/plastic bottle sorting. As in the first application setup, the plastic flakes were placed on the moving plate of the test setup, illuminated with the Fast Medium Wave IR illumination. The analysis and classification were likewise carried out using the BlackStudio software.

Figure 9: Photo of reference samples

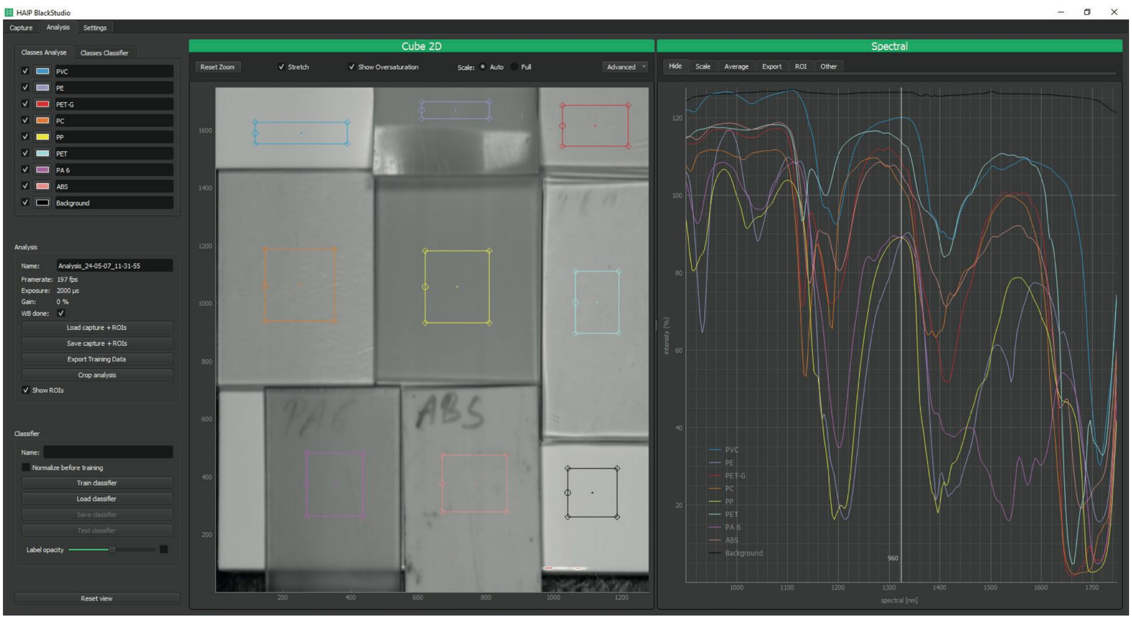


Figure 10: Screenshot BlackStudio software

7. Analysis BlackIndustry SWIR 1.7 Max

7.1 Results Reference Samples SWIR

Excerpts from the BlackStudio software are shown below. The left image shows the recorded plastic plates in greyscale format, as a 2D image. The colored rectangles (Regions of interest, ROI) mark the areas from which the spectral signature curves are extracted. The result of the classification is shown on the right-hand side. The category colors correspond to the ROIs.

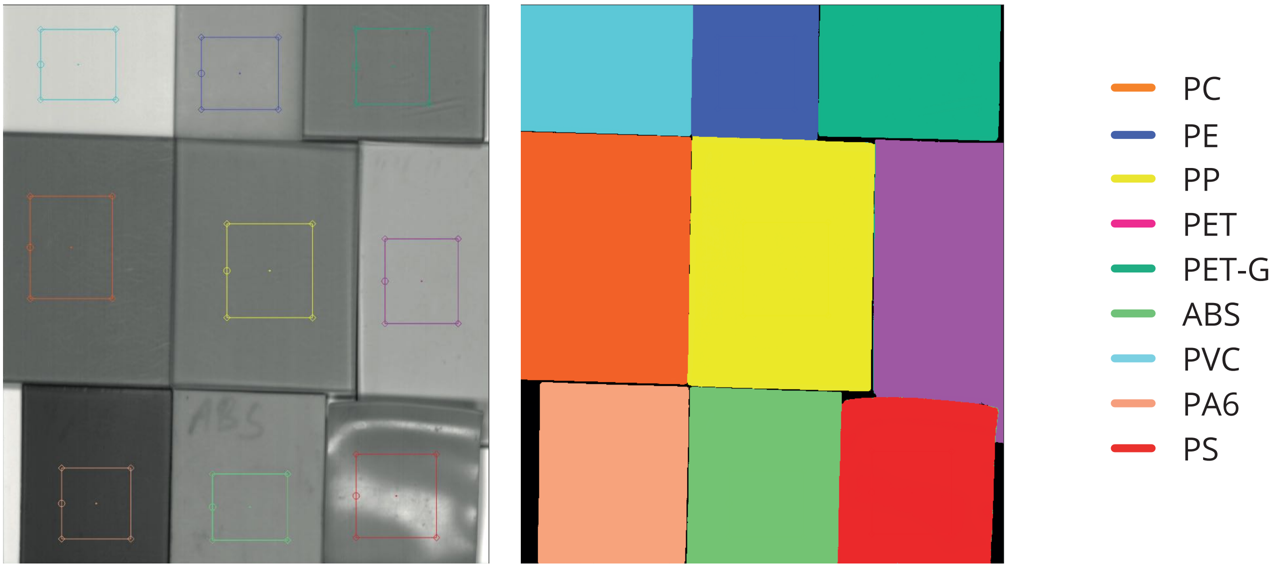


Figure 11: Recording reference samples BlackIndustry SWIR 1.7 Max with ROI markers for the training areas of the classification model

All plastic samples were easily differentiated because of their characteristic and unique absortion bands. The resulting spectral signatures of the plastic types over the entire wavelength range of the BlackIndustry SWIR 1.7 Max camera are shown in the following figure.

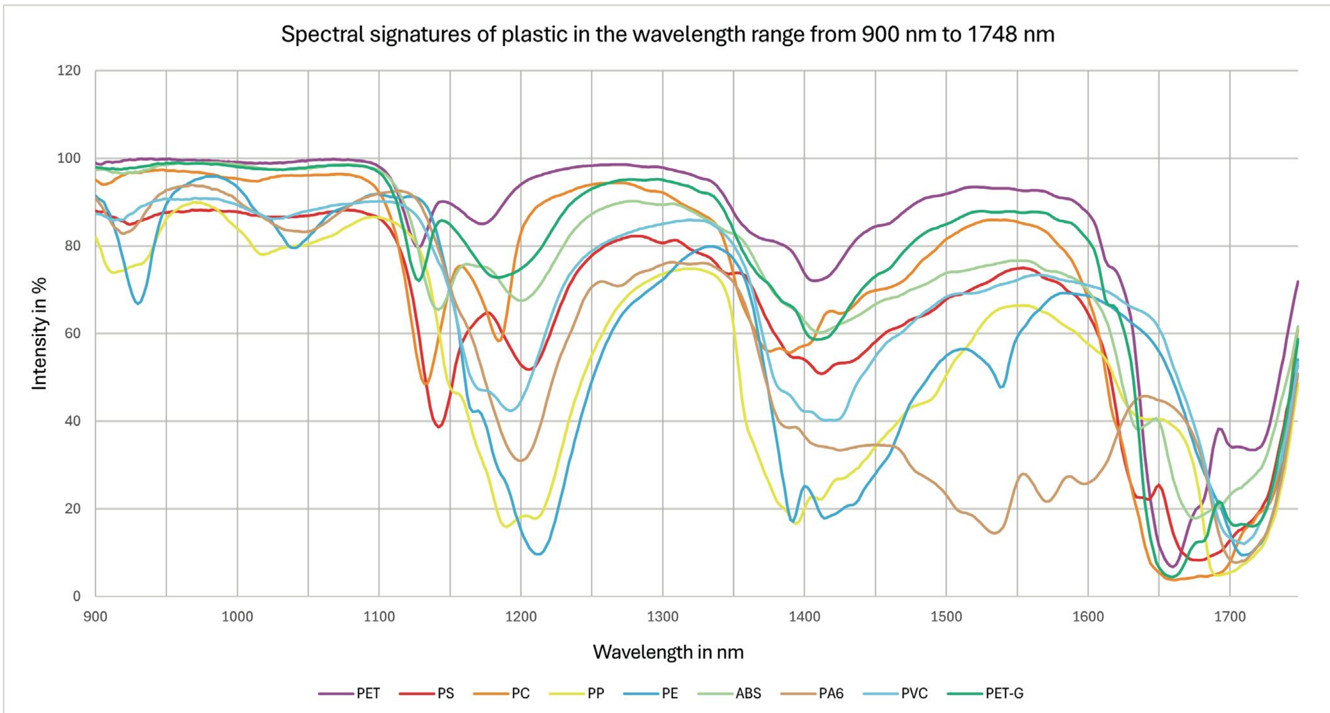
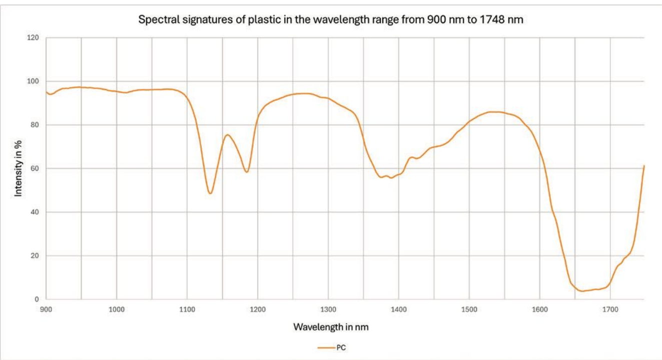
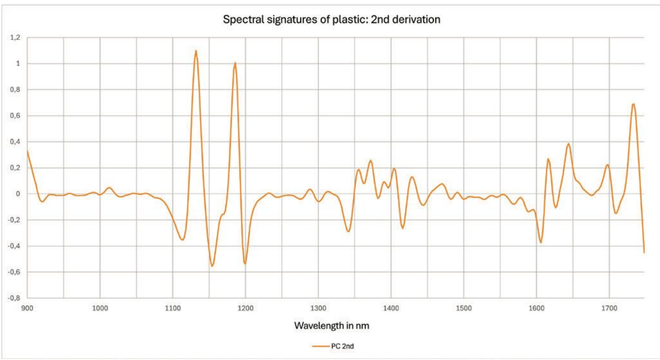


Figure 12: Spectral signatures of plastic in the wavelength range from 900 to 1750 nm

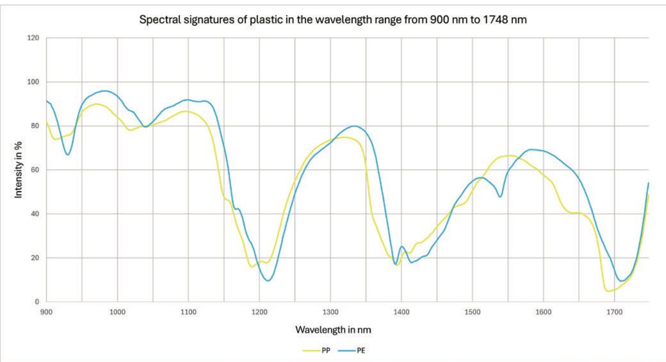
For the analysis, the reference spectra are split according to plastic types. The second derivative of the spectra is also visualized:

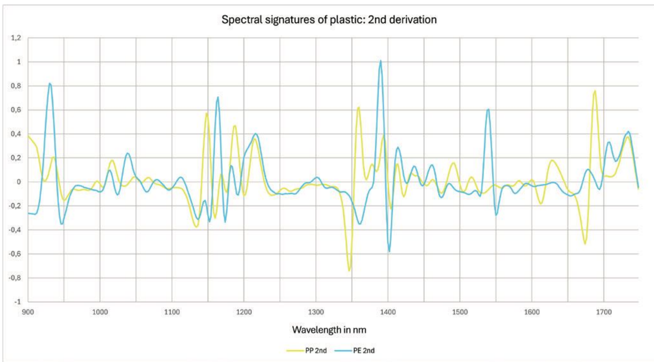
Transparent Plastics: Polycarbonate/**PC**



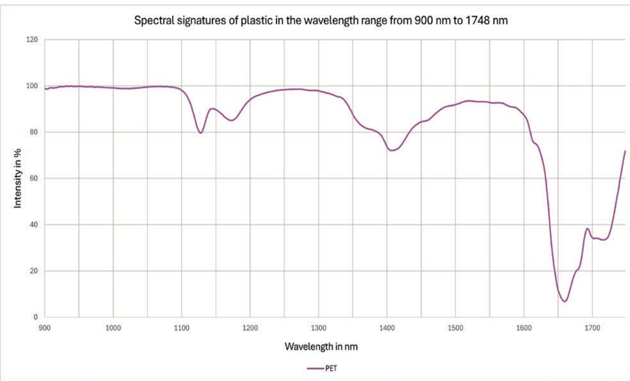


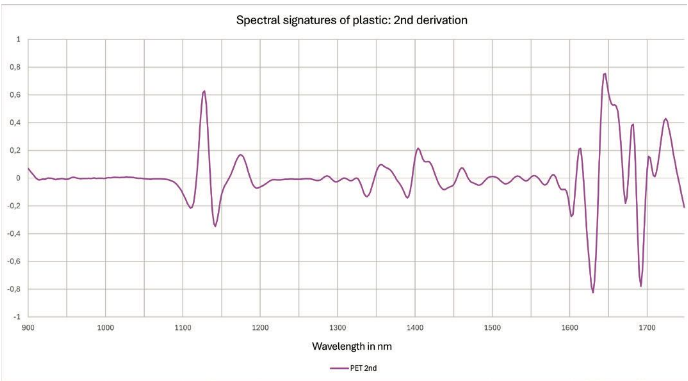
Polyelfines: Polyethylene/**PE**; Polypropylen/**PP**



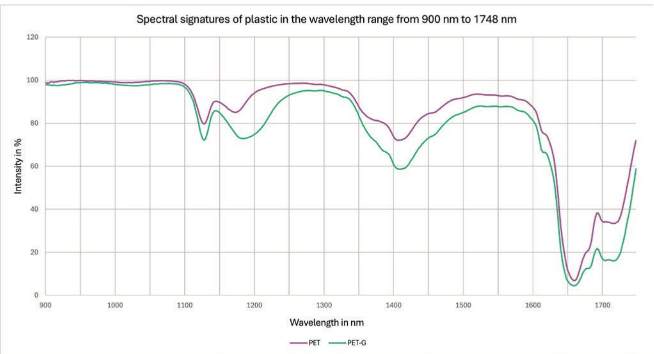


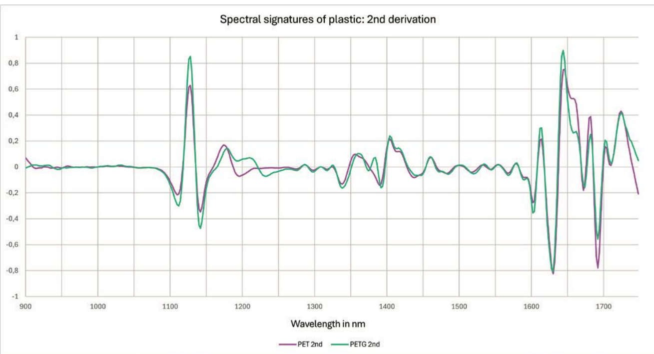
Transparent Plastics: Polyethylene Terephthalate/**PET**



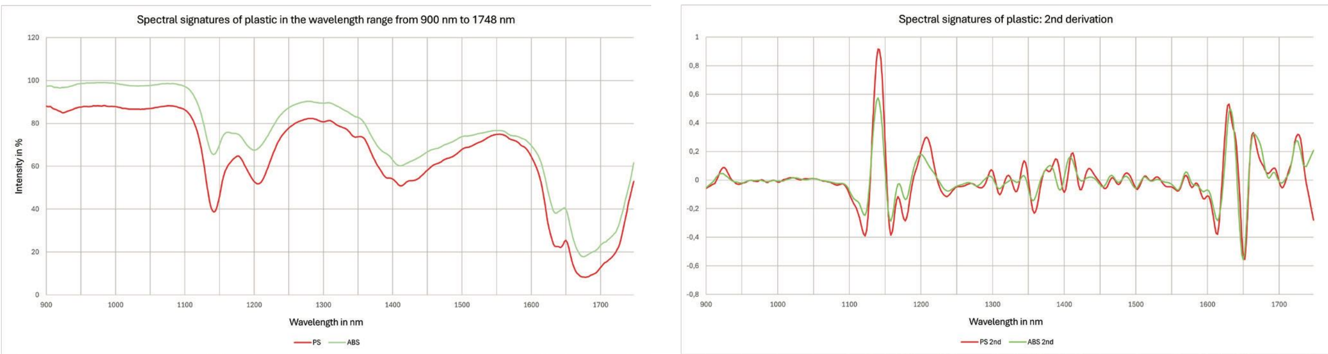


Transparent Plastics: Polyethylene Terephthalate/**PET**/**PET-G**

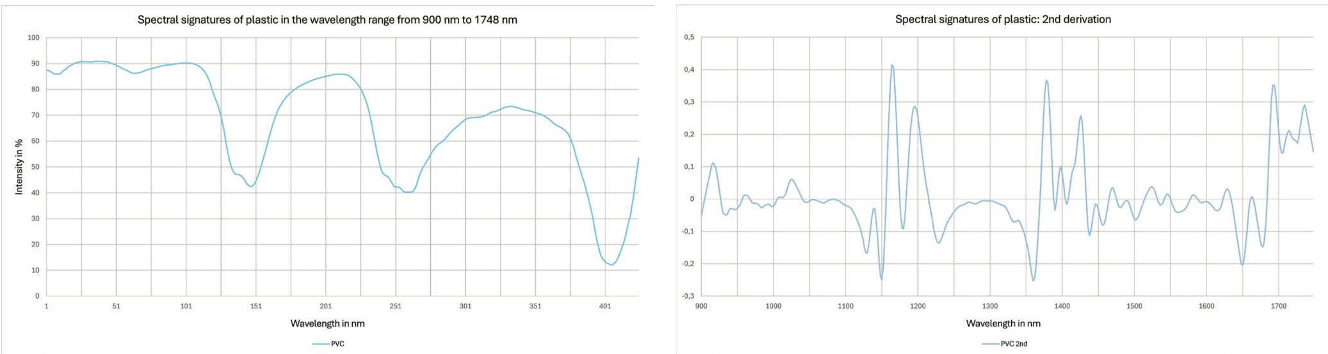




Styrenes: Acrylonitrile-Butadiene-Styrene/**ABS**; Polystyrene **PS**



Polyvinyl Chloride/**PVC**



Overview

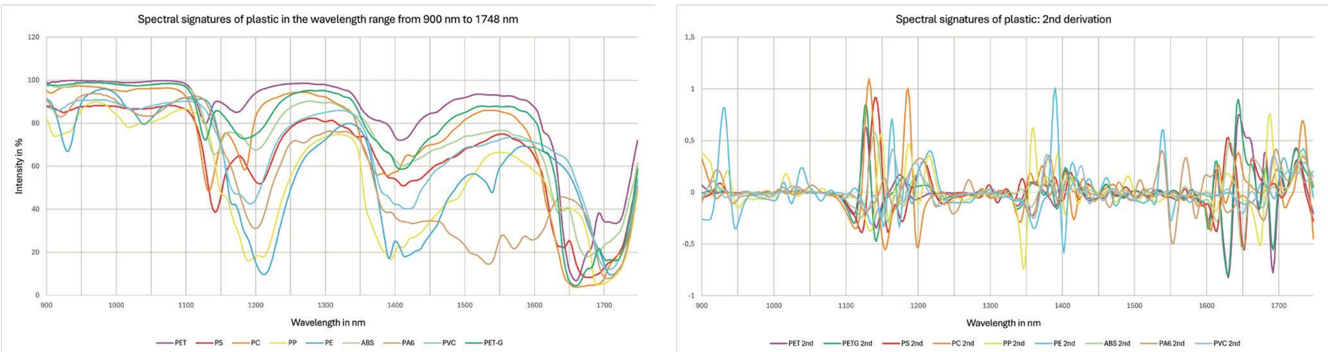


Figure 13: Classification of reference samples BlackIndustry SWIR 1.7 Max

7.2 Results Plastic Flakes SWIR

The 2D image of the recorded plastic flakes is also displayed in greyscale with ROIs marked in color. The classification results are shown below.

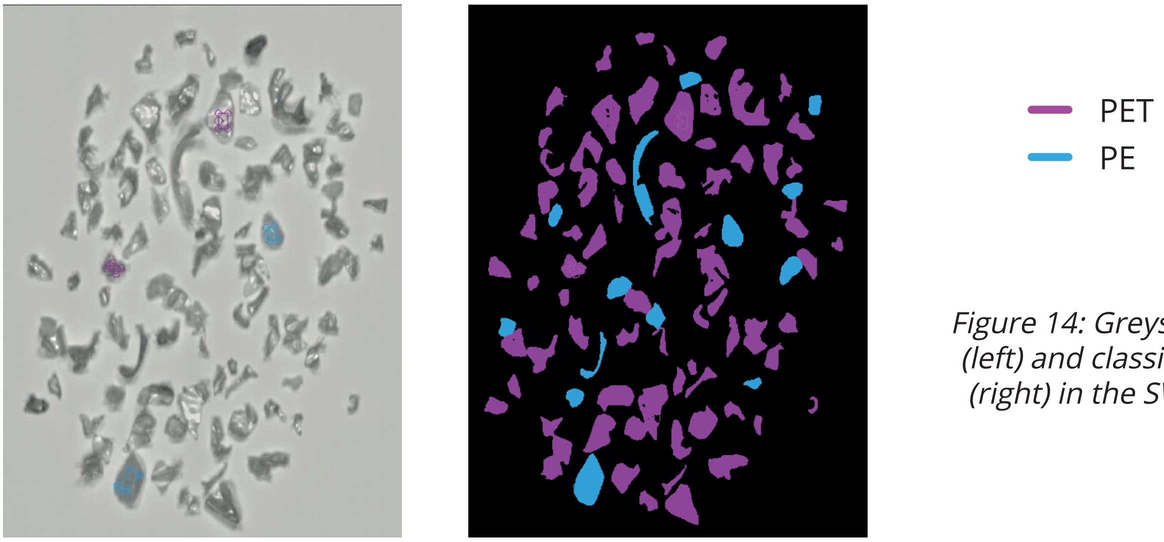


Figure 14: Greyscale image (left) and classified image (right) in the SWIR range

The classification results show without further object processing and edge corrections a fully stable and correct classification of the flakes.

8. Analysis BlackIndustry NIR

8.1 Results Reference Samples NIR

The hyperspectral data cube created with the BlackIndustry NIR camera is displayed in greyscale as a 2D image. The marked ROIs form the basis for the adjacent classification. For the classification, the spectral range of the BlackIndustry NIR is restricted to 800 - 1050 nm in order to ensure that the classification models are not influenced by color.

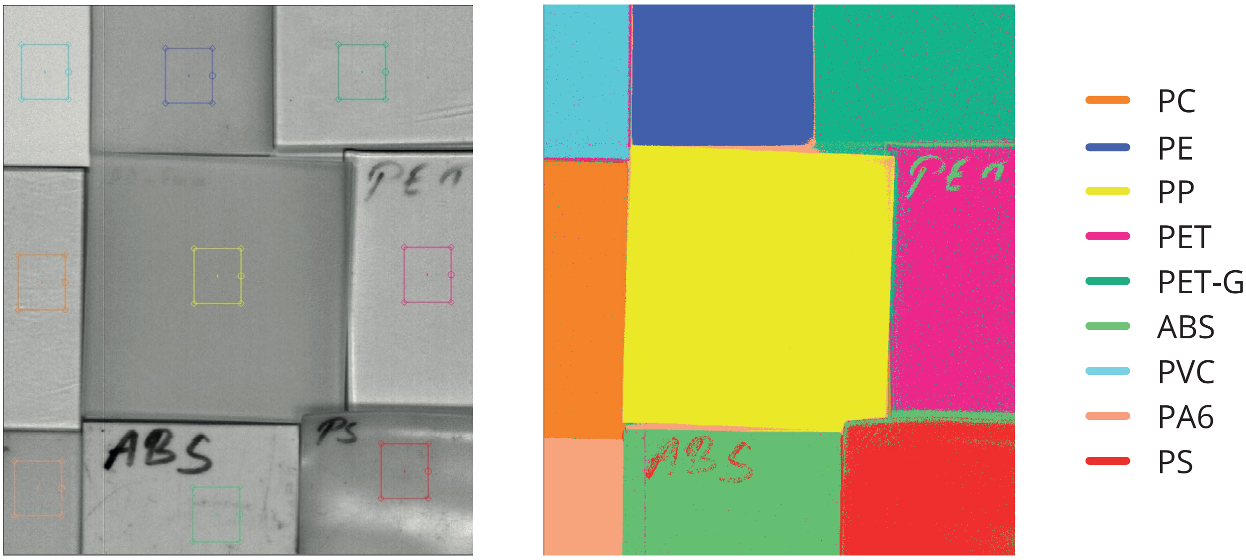


Figure 15: Recording reference samples BlackIndustry NIR with ROI markers for the training areas of the classification model

The BlackIndustry NIR has a very high spatial resolution, which can be clearly recognized by the level of detail of the 2D image. Furthermore, the high sensitivity and the good S/N ratio also allow the spectral absorption bands to be recognized significantly, even with the depth of absorption being not that big.

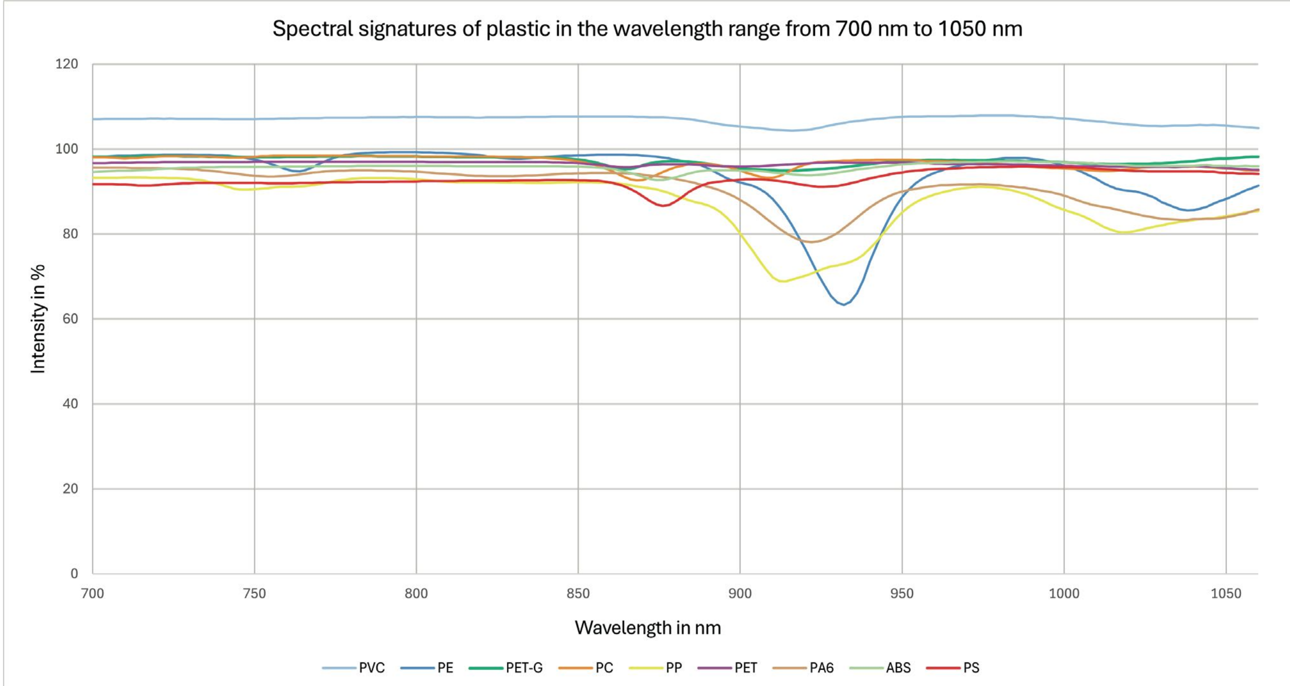
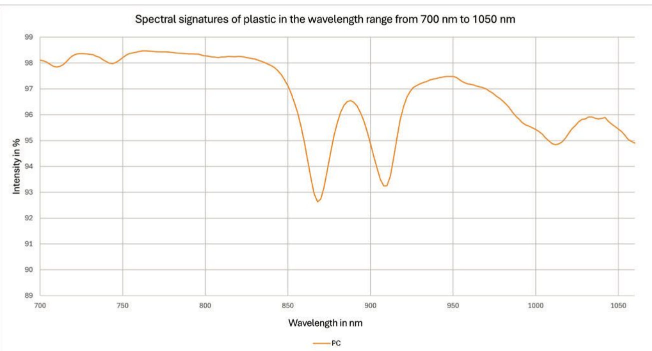
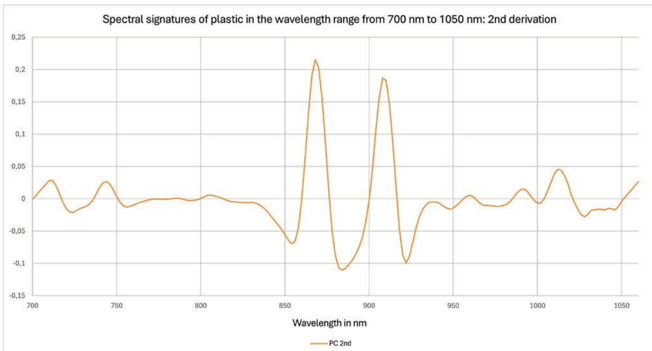


Figure 16: Spectral signatures of plastic in the wavelength range from 800 to 1050 nm

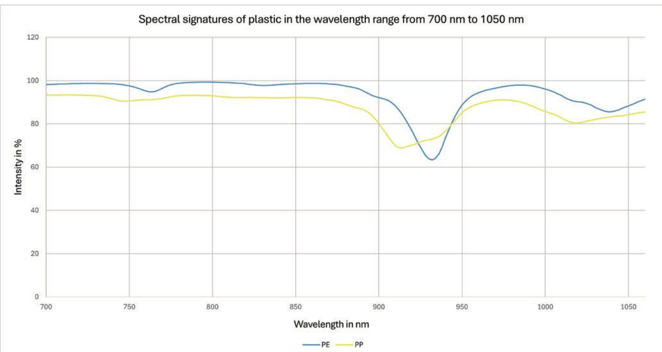
The following shows the reference spectra, recorded with the BlackIndustry NIR, divided according to plastic types, as well as their second derivation.

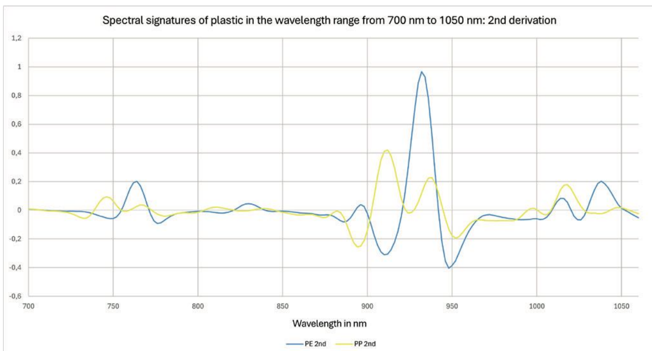
Transparent Plastics: Polycarbonate/**PC**



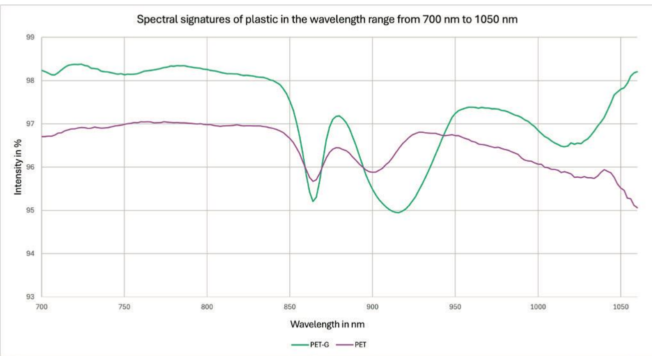


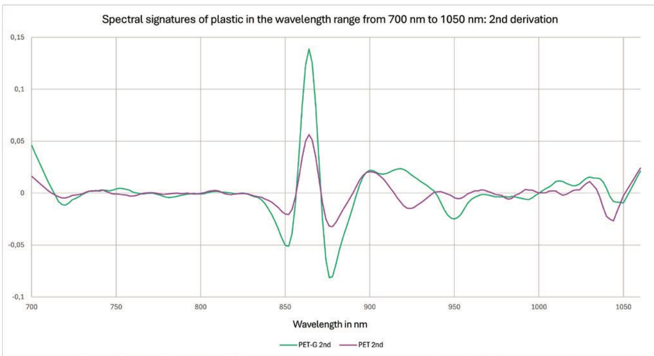
Polyelfines: Polyethylene/**PE**; Polypropylen/**PP**



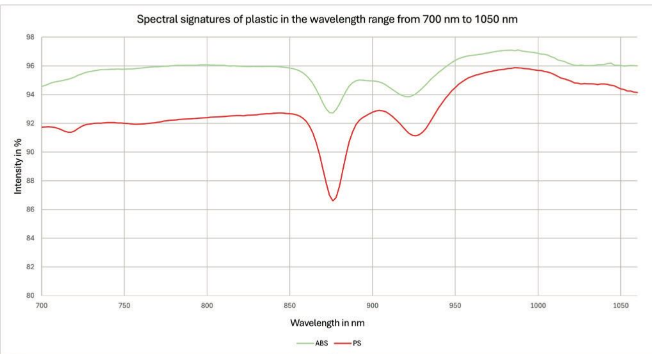


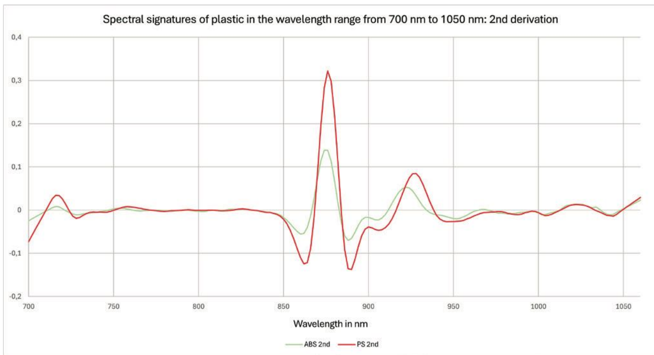
Transparent Plastics: Polyethylene Terephthalate/**PET**/**PET-G**



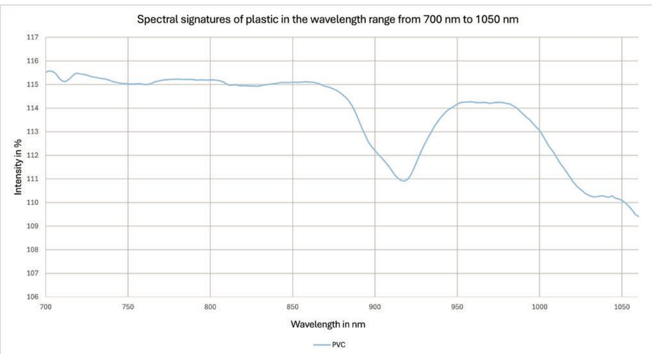


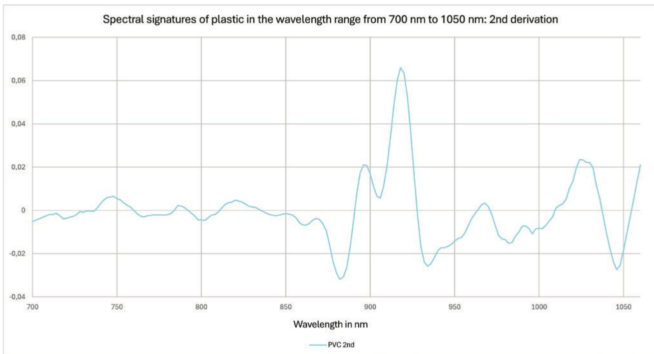
Styrenes: Acrylonitrile-Butadiene-Styrene/**ABS**; Polystyrene **PS**



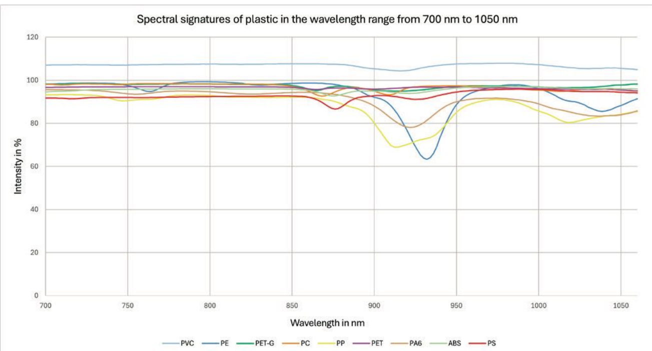


Polyvinyl Chloride/**PVC**





Overview



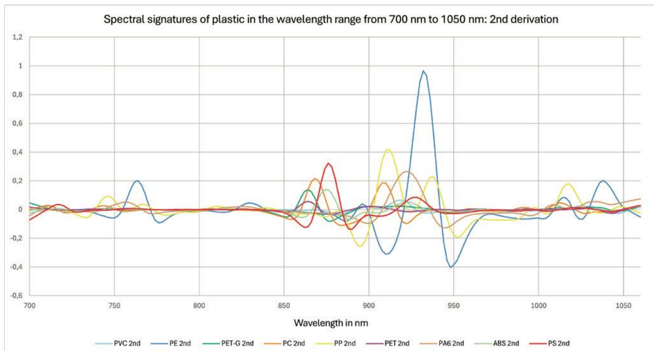


Figure 17: Classification of reference samples BlackIndustry NIR

8.2 Results Plastic Flakes NIR

The plastic flakes made of PE and PET were recorded by the BlackIndustry NIR camera and are shown below as a greyscale 2D image. The individual flakes have been recorded with sharp separation, so that not only a classification but also a segmentation for further analysis is possible.

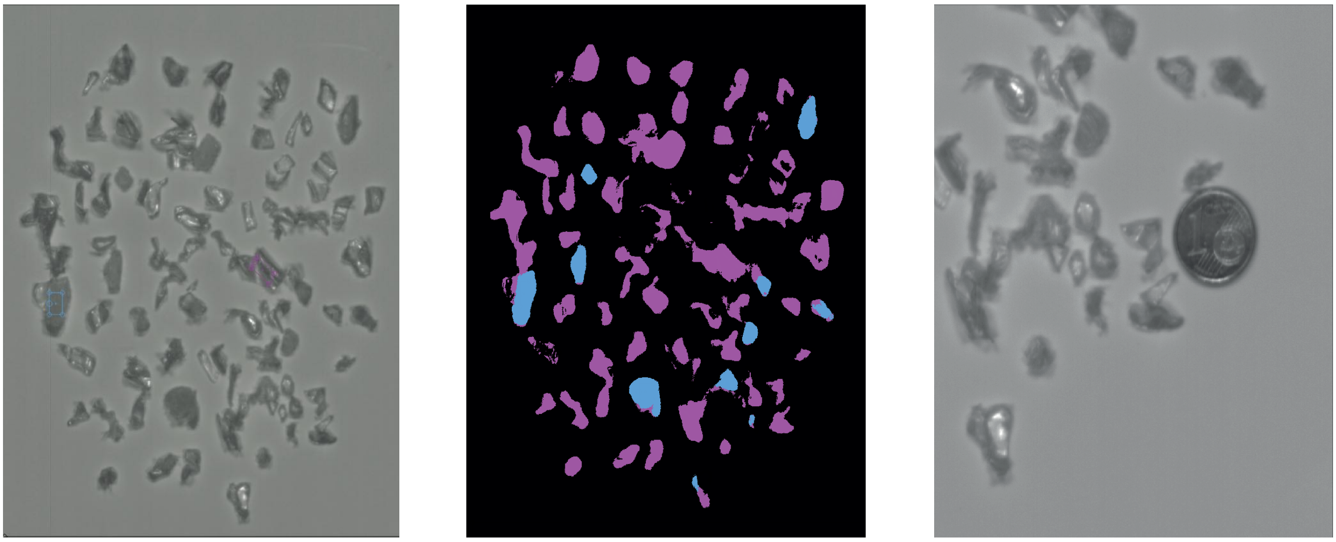


Figure 18: Greyscale image (left), classified image (middle), zoom image (right) of plastic flakes in the NIR range

PET　　PE

For the classification, the considered spectral range was limited to 820 - 1040 nm, in which the absorption bands of the plastics are located. The classification demonstrates the proper differentiation of the flakes. However, it should be noted that thin transparent PET flakes are very difficult to classify, as the absorption bands of PET are relatively weak compared to other plastics, and the low material thickness, transparency and reflective surface properties of the material present a challenge. In addition to chemometric classification, other conventional image processing methods should be used for a realistic sorting application.

9. Summary

For both camera systems (BlackIndustry SWIR 1.7 Max and BlackIndustry NIR), all plastic types can be precisely classified based on their characteristic absorption bands. In the SWIR range, the absorption signals are significantly stronger than in the NIR range. The absorption of the reference samples in the range from 1600 – 1750 nm accounts more than 80 % of the radiation. This also enables the identification of materials that are difficult to detect, such as:

- Very thin plastics (foils)
- Polluted plastics
- Deformed samples with oversaturated areas
- Dark samples with less reflected signal

In the NIR range, all relevant plastics exhibit a characteristic absorption band. As already mentioned, the signals are significantly weaker. It is therefore recommended to optimize the measuring conditions in this range. The optimizations include the following:

- The illumination must be arranged in such a way that as few specular reflections as possible appear
- The background should be designed in such a way that the signals originate directly from the transflective arrangement (bright background directly behind the objects)
- After the classification and before the sorting decision, it is beneficial to perform an object evaluation of the samples, so that the classification decision is not only derived from individual spectra

The following table provides an overview of the identifiability of typical plastics with the BlackIndustry systems:

	NIR (700-1050 nm, CMOS)		SWIR 1.7 (900-1750 nm, InGaAs)	
	Light Backround	Black Background	Light Backround	Black Background
PE	✓	✓	✓	✓
PP	✓	✓	✓	✓
PS	✓	✓	✓	✓
ABS	✓	✓	✓	✓
PVC	✓	✓	✓	✓
PET/PETG	✓	✓	✓	✓
PC	✓	✓	✓	✓
PMMA	✓	✓	✓	✓
PA	✓	✓	✓	✓

Figure 19: Overview of identifiability of plastics with BlackIndustry systems

Classification models were created in the BlackStudio software based on the reference samples. These models can be used directly for sorting in a further step. As the sorting must take place in real time and further parameterization or conventional image processing are ecommended for sorting, it is possible to use the BlackStudio software with a real-time module, which can be installed in the control cabinet of a sorting machine.

10. Conclusion

HAIP Solutions specializes in intelligent hyperspectral imaging camera systems that address a well-defined field of application in the best possible and most cost-effective way. As a result, the applications and fields of use are constantly expanding.

With the hyperspectral cameras of the BlackIndustry series and the extended tools for classification and sorting decisions, the barriers for the implementation of sorting applications based on hyperspectral technology are now overcome. The BlackIndustry cameras are affordable, offer a high spatial resolution, high frame rates and cover an extensive spectral range, making them unmatched by any other hyperspectral system. Even very small objects such as plastic particles can be identified, especially in the food industry. The low price resulting from the use of inexpensive CMOS image sensors in the BlackIndustry NIR camera is decisive for economic efficiency in industrial applications.

Contact us and together we will find the perfect hyperspectral solution for your application!

11. List of References

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