Advances in Near-Infrared Hyperspectral Imaging for Black Polymer Sorting in the Recycling Industry

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Abstract

Black plastics remain a critical challenge in automated polymer recycling due to the strong absorption of near-infrared (NIR) radiation by carbon-black pigments, which makes them impossible for conventional NIR-based sorting systems to identify by polymer type (Maier et al., 2024). Recycling and reuse of polymers from end-of-life vehicles (ELVs) have become a regulatory priority under the revised EU ELV Regulation (European Commission, 2023), which mandates higher recovery rates and the incorporation of at least 25% recycled plastic in new vehicles, including a defined share derived directly from ELV sources. Improved black-polymer detection, through MWIR or newly developed NIR hyperspectral imaging, is therefore critical to enable high-purity recovery streams and meet forthcoming EU material-circularity thresholds.

Until now mid-wave infrared (MWIR; 2.7 - 5.3 µm) hyperspectral imaging (HSI) has provided a promising solution by exploiting molecular vibrational features located in fundamental and combination absorption bands that remain accessible despite carbon-black pigmentation. Pioneering work by Rozenstein, Puckrin, and Adamowski (2017) first demonstrated that MWIR spectra contain diagnostic polymer-specific fingerprints, enabling discrimination of polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), and polyvinylchloride (PVC) even in black variants. More recent benchmarking by Roming et al. (2025) compared MWIR and NIR HSI

for mixed post-consumer streams and reported 30 - 40 percentage-point gains in balanced accuracy for black items using convolutional neural networks (CNNs), while maintaining near-industrial throughput rates.

Comparatively, Larsen et al. (2024) showed that long-wave infrared (LWIR) emission spectroscopy can also separate certain black plastics through emissivity contrasts, but the approach requires controlled temperature conditions and exhibits lower chemical specificity than MWIR absorption signatures. Beyond the infrared domain, Cielecki et al. (2023) demonstrated terahertz time-domain spectroscopy (THz-TDS) for black plastic identification, highlighting its insensitivity to carbon black but noting limitations in acquisition speed, cost, and integration into high-speed conveyor systems. Complementary optical techniques, such as Raman and laser-induced fluorescence (LIF) or laser-induced breakdown spectroscopy (LIBS) provide high specificity but are constrained by safety and throughput considerations (Bonifazi et al., 2023).

Remaining barriers for MWIR HSI include high sensor cost and cooling requirements for the detector which impose complexity and short lifetime in industrial applications. Over the past three years, new further developed sensor technologies have evolved and created the foundation for a third generation of imaging spectrometers in sensor-based sorting. HAIP Solutions has introduced the BlackIndustry SWIR 1.7 (950-1750 nm) camera series in summer 2023 providing now a never-before-seen spatial resolution of 2560 spatial pixels in a hyperspectral camera for the SWIR range. Having a higher spatial resolution NIR-hyperspectral cameras available, also makes using moving-average filter in preprocessing of spectral data possible, which enables increase of SNR and smoother spectral signatures for the polymer identification within complex sorting tasks, like thin-films or black polymers.

Next to the higher spatial resolution is also the increased sensitivity in the 1600-1750 nm region into the third overtone region of polymer absorption. In this region, subtle vibrational features of C–H and C=O bonds become accessible, allowing partial differentiation of certain black or dark-colored polymers that were previously undetectable.

Combining these new developments with so called Fast Midwave IR emitter illumination with better fitting peak response at 1500 nm for SWIR range (900-1700 nm) in comparison to halogen at 1100 nm is of high importance for the detection of black polymers in this range. By increased sensitivity in the third absorption band of polymers, it will now be possible to separate different type of black polymers which has not been possible before. Preliminary industrial evaluations indicate that with special developed high-intensity illumination, these advanced NIR systems can now classify some black grades of for example PE, PP, PS/ABS, PC and PA thereby improving compatibility with existing NIR sorting infrastructure while offering a lower cost of deployment and industrial grade robustness compared to previous MWIR systems.

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