Hyperspectral Imaging for Sustainable Waste Recycling

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1. Hyperspectral Imaging in the Waste Recycling Sector

Waste management is a crucial global issue that affects both society and the environment. Thus, there is an urgent need for new recycling technologies that will provide innovative solutions for a more sustainable future. Recycling technologies can help reduce the quantity of waste sent to landfills while also preserving natural resources. Sorting and quality control processes are required to implement a proper and effective recycling process, but they can be labor intensive and sometimes time consuming.

Hyperspectral imaging (HSI) has emerged in recent decades in the waste recycling sector, allowing the identification of different materials based on their unique spectral signature [1]. HSI is non-destructive, spectral data to be captured across a wide range of the electromagnetic spectrum into a hyperspectral image cube [2,3]. A hypercube is a three-dimensional data structure (two spatial dimensions [X-Y] and one spectral [λ]), in which each pixel represents a spectrum [4]. Therefore, hyperspectral images are datasets containing a complete spectrum at each point in a spatial array [5,6].

The goal of HSI analysis is to extract chemical information from these typically high-dimensional datasets into a limited number of components that describe the sample spectral and spatial features.

The HSI-based approach is especially effective in quality control, allowing for the monitoring of recycled material quality and ensuring that it meets industry standards [7]. In more detail, an HSI-based quality control system allows for the detection of contaminants such as non-recyclable elements that degrade the quality of recovered products [8]. This kind of system helps to verify that recycled materials are appropriate for their intended application by identifying and characterizing their chemical composition.

The utilization of HSI in the waste sector can also improve the efficiency of sorting processes by (i) automating the identification and selection of waste materials and (ii) increasing the purity of recycled materials (i.e., removing contaminants that may negatively affect the quality of recycled products). Moreover, the use of HSI can reduce labor costs and increase throughput rates compared to traditional manual sorting methods [9].

Recent studies have demonstrated the potential of HSI in waste recycling [10]. A HSI-based waste approach can differentiate between various materials, including plastics, metals, glass, paper, and organic materials [11–13]. In particular, a successful application of the HSI concerns the possibility of identifying and separating the different types of plastics despite similar physical and morphological attributes (e.g., density), thus overcoming the limitations of traditional selection methods [1,10]. This quality is essential to the recycling process.

2. Hyperspectral Imaging Techniques

In recent years, many full-spectrum imaging techniques that promise rapid and complete chemical evaluation of complex, heterogeneous materials have been introduced.
A typical spectral image is created by moving a focused probe across a sample and measuring the probe/sample interaction with both spatial and spectral resolution [14]. Counting particles such as photons, electrons, and ions, etc., is a common method used to obtain spectra from the surface of analyzed materials; several imaging techniques, adopted in surface analysis and microanalysis, generate spectra by counting this kind of particle. Numerous physical principles can be used to generate multivariate data and/or hyperspectral images. In more detail, the variables in HSI images are related to signals measured in spectral channels, such as absorbance or reflectance in infrared imaging, or counts at certain mass channels in mass spectrometry, hence the term “spectral” was derived. HSI employs a variety of spectroscopy techniques, including infrared (IR), Raman and ultraviolet-visible (UV-Vis).

Optical devices such as spectrometers and cameras play a crucial role in HSI-based waste sorting and quality control. Spectrometers measure the intensity of light at different wavelengths, while cameras capture the spectral information of images. The combination of spectrometers and cameras in HSI devices enables the identification and sorting of waste materials based on their unique spectral signatures [15,16]. In fact, infrared sensors can detect differences in light absorption, transmission, and scattering at infrared wavelengths resulting from different materials. Typically, Near InfraRed (NIR, wavelengths: 700–1400 nm), Short-Wave InfraRed (SWIR, wavelengths: 1400–3000 nm), Medium-Wave InfraRed (MWIR or MIR, wavelengths: 3000–8000 nm), and Long-Wave InfraRed (LWIR or LIR, wavelengths: 8000–15,000 nm) are the four areas of the infrared spectrum. MIR and LIR approaches take longer to acquire than NIR and SWIR methods but provide better-defined spectrum information [15]. The acquisition of NIR and SWIR spectra, on the other hand, is faster, but it requires complex mathematical approaches, such as multivariate statistical analysis, to extract information about material components [17].

3. Recent Advances in HSI-Based Waste Recycling

The last advances in HSI in the waste recycling sector have focused on improving the accuracy and efficiency of waste sorting and quality control processes. One approach is the development of Machine Learning (ML) and Deep Learning (DL) algorithms that can analyze hyperspectral data and automatically classify materials based on their spectral signatures [18,19]. ML and DL algorithms can be trained using large datasets of spectral signatures, enabling the accurate identification and sorting of waste materials.

ML and DL are both categories of Artificial Intelligence (AI). In brief, ML is an AI that can automatically adapt with minimal assistance from humans. DL is a particular form of ML, and it refers to that branch of AI that refers to algorithms inspired by the structure and function of the brain, and replicating how the human brain learns, called Artificial Neural Networks (ANNs). ANN, Convolutional Neural Network (CNN), Decision Trees (DT), Naïve Bayes, k-means clustering, k-Nearest Neighbor (k-NN), Support Vector Machines (SVM), and Random Forest (RF) are among the most popular techniques used to manage multivariate datasets [18]. Image recognition and classification are the most common applications of ML and DL.

The advancements in the mechatronic field also allowed the integration of HSI devices with robotic systems in the recycling/waste sector. Such systems, adopting ML and/or DL logics, can use HSI data to identify, sort, and control the quality of recyclable materials automatically, increasing the efficiency and accuracy of the waste treatment processes [20,21]. In this context, robotic sorting systems can also be used to sort hazardous waste, lowering the risk of human exposure to health-harmful substances.

The Special Issue “Hyperspectral Imaging for Sustainable Waste Recycling” aims to explore new frontiers in the sector and to demonstrate the importance of implementing HSI-based systems in the waste recycling field, as well as to discuss current achievements in the field.

Conflicts of Interest: The authors declare no conflict of interest.
References


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