Hyperspectral Imaging Algorithms and Applications: A Review

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Abstract

The paper covers topics ranging from hyperspectral imaging applications to innovative algorithms that have enhanced the analysis of hyperspectral data. We delve into the practical applications, including Agriculture, Food Quality and Safety, Earth Sciences, Exploration and Monitoring, Healthcare, Pharmaceuticals, Medical Imaging, Industrial Manufacturing, Management, Conservation, Safety and Security. Our goal is to provide a holistic understanding of how hyperspectral imaging is transforming these fields and driving new possibilities. We also discussed detailed algorithmic development in Hyperspectral Imaging including Supervised and Unsupervised algorithms. We reviewed algorithmic development from the early 1980s to recent developments including Artificial Intelligence involving algorithms from Machine Learning to Deep Learning. We believe our paper will be of particular interest to your readers for those who wish to study algorithm development from simple image processing procedures to AI based approaches and how these algorithms are used in diverse applications to make intelligent decisions for increasing productivity and efficiency in Agriculture, Exploration and Management and identification of diseases and natural resources. Our paper is well organized into various sections as per algorithms and applications. We reviewed more than 250 papers with proper citations and authors’ research work.
Hyperspectral Imaging Algorithms and Applications: A Review

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Abstract—Hyperspectral Imaging (HSI) provides detailed spectral information for each pixel in an image, which involves acquiring images at numerous narrow and contiguous wavelength bands. Comprehensive spatial and spectral information deposits in hyperspectral images acquired by sensors, cameras, and various data acquisition sources lead to a wide range of applications across multiple fields from agriculture, and environment to biology. Various Image Processing and Artificial Intelligence algorithms have been developed periodically to analyze the data acquired through HSI. This review paper presents a comprehensive analysis of HSI focusing on its various aspects and potential implications. We explore detailed applications and key algorithms of HSI and discuss the associated advancements and challenges. Through an extensive literature review, we identify the state of research and methodologies related to HSI. Our study covers a wide range of HSI applications such as Earth Sciences, Exploration, Monitoring, Agriculture, Security, Conservation, Security, Healthcare, and Medical Imaging, and how Hyperspectral Imaging algorithms benefit these applications. Additionally, we discuss emerging trends and future directions in HSI providing insights into the promising avenues for further research.


I. INTRODUCTION

HYPERSONSPECTRAL Imaging (HSI) combines the power of digital imaging with a chemical technique called spectroscopy meaning it can collect and process information from across the electromagnetic spectrum far beyond visible light by measuring how light is reflected at hundreds of continuous wavelengths. It is becoming increasingly more relevant because of certain trends like the rapid decrease in the size of hyperspectral sensors, the parallel decrease in the cost of computation, and the exponential increase in Image Processing power. HSI could signify a big shift in helping to quantify the world.

The spatial information of an image, plus the chemical discrimination of spectroscopy combine to make hyperspectral a very powerful measurement technique as shown in Figure 1. HSI is a powerful technology that capitalizes on the unique chemical “fingerprint” inherent in all objects. This technique relies on the fact that similar objects share similar spectral characteristics. Various materials, such as minerals, vegetation, and building materials, interact with light by reflecting and absorbing different wavelengths in distinct ways. Hyperspectral sensors are designed to precisely detect these spectral variations, enabling the capture of fine details that surpass the capabilities of traditional RGB imaging. This technology provides a wealth of information by collecting dense and continuous spectral data for each pixel in an image. The data acquired through HSI is stored in a hypercube, essentially a stack of images of the same object or scene, with each image corresponding to a specific wavelength. To unlock the full potential of hyperspectral data, specialized analysis software is required to manipulate the hypercube effectively. In essence, HSI offers a comprehensive view of the world, capturing full-resolution spectral signatures that open doors to a wide range of applications and insights.

HSI offers a multitude of compelling reasons for its utilization. One key advantage lies in its capacity for quantification, enabling the precise determination of material abundance within a given scene. Moreover, HSI excels in material characterization by assessing the variability of identified substances. For instance, it can differentiate between wet and dry sand or discern the effects of soil particle size. Discrimination is another valuable aspect, as HSI can ascertain the unique identity of diverse generic categories of materials which identifies materials and distinguishes them. Furthermore, HSI plays a pivotal role in classification by segregating materials into spectrally similar groups, facilitating more nuanced categorization. HSI also serves as a powerful tool for target detection. It can determine the presence of specific materials, objects, activities, or events of interest within a given scene. This capability makes it an invaluable asset in various fields, from remote sensing to environmental monitoring and beyond.
HSI, initially designed for remote sensing purposes around 1980, has witnessed a progressive expansion of its applications over the past two decades. It has found utility in a wide range of agricultural and food research domains, facilitating the simultaneous acquisition of valuable data related to images and the chemical composition of various research subjects [2]. One of the important aspects of HSI is data acquisition which takes images of targets using HSI Platforms and Sensors [1]. Satellite-Based HSI, Airplane-Based HSI, UAV-Based HSI and Close-Range (Ground- or Lab-Based) [1] HSI are some of the sensors which are used to acquire the data. Various algorithms are applied for retrieving information from the data acquired after image preprocessing. Typical processing of hyperspectral imagery includes geometric correction, orthorectification, radiometric correction, and atmospheric correction [1]. Many methods for processing and analyzing Hyperspectral Images are developed over a period of time such as atmospheric effects removal, imaging spectroscopy, dimensionality reduction, image classification, mixture modeling, sub-pixel class, super-resolution principles, empirical relationships, adative transfer modeling, machine learning, and deep learning [1][3]. Figure 2 shows the timeline of HSI algorithms and applications starting from core Image processing algorithms to advanced algorithms of artificial intelligence, Image Enhancement techniques like Histogram Equalization, Convolution, Spatial Filtering, Fourier Transform, Wavelet Thresholding, Pseudo-coloring, and Arithmetic Operations [4] are efficient techniques for enhancing hyperspectral images. Unsupervised algorithms for Image Segmentation and Object Measurement like Thresholding, Morphological Processing, Edge-based Segmentation, Spectral image segmentation, Intensity-based measures, and Texture [4] are used to analyze the images. Hyperspectral Images are high-dimensional data, so it will be good to reduce the dimensionality to avoid redundant features. Principal Component Analysis (PCA) [3] and other techniques are used for feature extraction and selection. Hyperspectral image processing and analysis algorithms can be broadly classified into supervised and unsupervised methods [5], depending on their reliance on labeled training data. Table 1 shows different Unsupervised and Supervised algorithms for Hyperspectral Image Processing [6] analysis and classification.

HSI, an advanced technology, has diverse applications spanning a wide array of fields. It grants valuable insights into our surroundings by collecting data across numerous narrow, adjacent spectral bands. Within agriculture [1][2], it supports activities like evaluating crop health, detecting diseases, and analyzing nutrient levels, thus promoting sustainable farming practices. Environmental experts rely on it to monitor water quality, identify sources of pollution, and assess the health of ecosystems. In the healthcare sector, HSI assumes a pivotal role in medical diagnostics, delivering precise tissue analysis and early disease identification. Industries benefit from it for quality control, defect detection, and infrastructure assessments, ensuring the integrity and safety of products. Geology and mineral exploration benefit from its capacity to unveil subterranean mineral reserves and geological characteristics, contributing to resource management. Furthermore, HSI extends its impact to heritage preservation, space exploration, and more, establishing itself as a versatile tool with an influence on various facets of our lives. Moreover, it proves invaluable in mineral exploration by facilitating the identification of mineral composition during geological surveys. and have demonstrated its potential for clinical applications [7]. Figure 4 shows different HSI applications in wide areas.

II. HYERSPECTRAL IMAGING ALGORITHMS

A. Algorithms Used

Hyperspectral imaging (HSI) stands as a cutting-edge and potent technology with wide-ranging applications across multiple domains, encompassing remote sensing, agriculture, geology, and medicine. Diverging from conventional imaging...
systems that capture a mere trio of color channels (red, green, and blue), HSI captures an extensive array of closely spaced spectral bands spanning the electromagnetic spectrum. Within a hyperspectral image, each pixel comprises a comprehensive spectrum, facilitating intricate material analysis based on their distinctive spectral signatures. This abundance of spectral data offers valuable insights into object composition, structure, and characteristics, establishing HSI as a versatile tool for diverse tasks like material identification, disease diagnosis, environmental surveillance, and more. Within this context, numerous HSI algorithms have been developed to extract meaningful information and patterns from hyperspectral data, significantly elevating our capacity to scrutinize and comprehend intricate scenes with remarkable precision.

The Spectral Angle Mapper (SAM) [12][18][44][57][217] algorithm is employed in hyperspectral image analysis to compare spectral data, making it valuable for tasks like image classification and target detection. SAM evaluates the similarity between a pixel’s spectral signature and a reference spectrum by calculating the angle between them. This process involves treating these spectral signatures as multi-dimensional vectors. The angle measurement reflects the degree of similarity, with smaller angles indicating closer matches. SAM categorizes pixels based on this angle, designating those with values below a set threshold as the target material and the rest as something else. It’s adept at discerning spectral distinctions, making it well-suited for identifying materials with known spectral signatures. In summary, SAM aids in the classification or detection of specific materials or targets within hyperspectral images.

Hyperspectral image classification involves categorizing pixels into predefined classes, with Random Forest [9][60][69][113][209][213][221] and Binary Logistic Regression [9] being commonly used methods. Random Forest is effective for handling high-dimensional data, employing ensemble learning to capture complex spectral patterns. In contrast, Binary Logistic Regression is a straightforward yet effective approach for binary classification, providing a clear probabilistic interpretation. The choice between these methods depends on specific task requirements, data complexity, class count, and result interpretability. Support Vector Machine (SVM) [22][42][57][69][127] is a powerful machine learning algorithm widely applied in HSI for classification tasks. SVM aims to find a hyperplane that optimally separates different spectral classes in high-dimensional hyperspectral data, making it effective for tasks like land cover classification and anomaly detection. Its ability to handle complex, non-linear relationships in data through kernel functions enhances its versatility in hyperspectral analysis.

In [9] authors combine 3D hyperspectral mapping in the SWIR spectrum with a UAV-derived DEM to analyze a carbonate rock outcrop. The integrated 3D geological model reveals rock formations, including thickness, slope, classification, strike, and dip. A SWIR hyperspectral camera with 288 spectral channels was used, and preprocessing techniques like Savitsky-Golay filter, dark subtraction, and MNF transformation were applied. The Random Forest algorithm achieved high accuracy in classifying limestone and dolostone, while Binary Logistic Regression demonstrated better generalizability. Challenges included shadows on the uneven rock surface and their impact on 3D point cloud quality during image feature matching.

In [12] authors used the Digital outcrop models technique for detailed geologic studies, which are produced by understanding hydrocarbon reservoir properties and enhancing subsurface models. The hyperspectral images were classified using the Spectral Angle Mapper (SAM) image processing algorithm. Multiple linear regression [13][207] and partial least squares (PLS) [13][15][68][74][75][207] in HSI involve modeling the relationship between multiple spectral bands and a specific target variable, such as chemical composition or material properties. By considering the linear combinations of spectral bands and exploiting latent variables, PLS enhances the predictive power, making it a valuable tool for quantitative analysis in hyperspectral remote sensing. These techniques enable the prediction or estimation of the target variable, providing valuable insights into various applications like agriculture, environmental monitoring, and mineral exploration.

In HSI, keypoint detection [14] algorithms play a crucial role in identifying distinctive points or features within the spectral data. These keypoints serve as reference points for subsequent analysis and processing. Point-matching [14] algorithms, on the other hand, are employed to establish correspondences between keypoints in different hyperspectral images, allowing for tasks like image registration and change detection.

SIFT (Scale-Invariant Feature Transform) [9] is a widely used keypoint detection algorithm that can identify robust and distinctive keypoints across different scales and orientations. It has been adapted for HSI to facilitate feature-based analysis. Point Cloud [9], in the context of HSI refers to a collection of 3D points representing the spatial distribution of keypoints [14] in a scene. This data structure is employed in tasks such as 3D reconstruction and scene understanding, where keypoints [14] are matched to create a coherent 3D representation of the hyperspectral scene. Together, these algorithms enable advanced analysis and interpretation of hyperspectral data for a wide range of applications, including remote sensing, geospatial analysis, and mineral identification.

In HSI, Decision Trees [60][69] are utilized as a machine learning algorithm for classification tasks. They work by recursively splitting the hyperspectral data into subsets based on spectral features, enabling the creation of a hierarchical decision structure to classify pixels into predefined categories or classes.

In HSI, dimensionality reduction techniques are essential for managing the high-dimensional data efficiently. Linear discriminant analysis (LDA) [15] and quadratic discriminant analysis (QDA) [15] are supervised methods that aim to reduce dimensionality while maximizing class separability, making them valuable for hyperspectral image classification.

Partial least squares-discriminant analysis (PLS-DA) [35][78] combines spectral information with class labels, allowing it to capture relevant features for classification tasks. Principal component analysis (PCA) [60][68][70][73][91][150] is an unsupervised method that
identifies orthogonal axes of maximum variance, effectively reducing noise and extracting significant features. K-means clustering [36] is a commonly used unsupervised technique in HSI for segmenting pixels into clusters based on spectral similarity, aiding in material identification and classification.

Minimum noise fraction (MNF) [9][29], orthogonal total variation component analysis (OTVCA) [20], and wavelet-based sparse representation with a regularized robust regression (WSRRR) [20] are advanced dimensionality reduction techniques tailored for hyperspectral data. MNF is particularly useful for noise removal, while OTVCA and WSRRR offer effective ways to extract relevant information while reducing data dimensionality. These techniques collectively enhance the analysis and interpretation of hyperspectral images.

In [24] authors introduce HESSC, a novel hierarchical sparse subspace-based clustering algorithm for HSI data. This algorithm addresses the challenges of high computational demands and predefined cluster numbers associated with existing methods. HESSC employs a hierarchical structure, utilizing sparse subspace-based binary clustering at different levels of detail. It also incorporates an entropy-based ensemble approach to enhance accuracy. Importantly, HESSC autonomously determines cluster numbers based on reconstruction error values, eliminating the need for manual predefined. Experimental results using real drill-core and benchmark hyperspectral datasets demonstrate the effectiveness of HESSC, positioning it as a valuable tool for hyperspectral image analysis compared to other clustering algorithms like K-means and FCM. In [60] authors explore the potential of using HSI and vegetation indices (VIs) to identify different species of woody plants. The analysis, including ANOVA, Principal Component Analysis (PCA), Decision Tree (DT), and Random Forest (RF) methods, consistently differentiated these species.

In [58] authors propose a method based on a look-up table (LUT)-based inversion of a radiative transfer model (RTM) to retrieve these vegetation parameters. They compared different cost functions for the inversion process and demonstrated the spatial and temporal consistency of their estimations over two years. In [219] authors proposed a classification method based on spectral information divergence to accurately identify mosaic-infected areas in sugarcane with high precision, demonstrating the effectiveness of this approach for disease detection in agricultural settings.

Deep Learning [8][40], including Artificial Neural Networks (ANNs) [15][69], Long Short-Term Memory (LSTM) [43] networks, and Convolutional Neural Networks (CNNs) [11][22][40][42][59], has revolutionized HSI analysis. These deep learning models can extract intricate spectral and spatial features from hyperspectral data.

**Artificial Neural Networks (ANNs):** ANNs consist of interconnected nodes, or neurons, organized into layers (input, hidden, output). Mathematically, the output of a neuron in a feedforward ANN [71] can be represented as a weighted sum of its inputs, followed by an activation function:

\[
y = \sigma(\sum (w_i x_i) + b)
\]

Training involves adjusting the weights and biases using backpropagation and gradient descent to minimize a loss function.

**Convolutional Neural Networks (CNNs):** CNNs [69][136][137] are specialized for spatial data, like images, by using convolutional layers. In CNNs, convolution is represented as:

\[
y(i, j) = (X * K)(i, j) = \sum m \sum n X(i-m, j-n)K(m, n)
\]

Pooling layers downsample the feature maps, reducing computational complexity. CNNs have been adapted to hyperspectral data, where the third dimension corresponds to spectral bands.

**Long Short-Term Memory (LSTM) Networks:** LSTMs [43] are a type of recurrent neural network (RNN) designed to capture sequential dependencies. Mathematically, LSTMs include a cell state, hidden state, and gates (forget, input, output), allowing them to remember and forget information:

\[
ft = \sigma(W_f.ht - 1, tx) + bf
\]

\[
it = \sigma(W_i.ht - 1, tx) + bi
\]

\[
ot = \sigma(W_o.ht - 1, tx) + bo
\]

\[
c = ft * ct + i*tanh(Wc.(ht - 1, tx) + bc)
\]

\[
h = ot*tanh(ct)
\]

LSTMs can capture temporal dependencies in hyperspectral sequences. Deep learning [40] in HSI involves adapting these models to process the multi-dimensional data efficiently. Researchers often design custom architectures or use transfer learning from pre-trained models to harness the power of deep learning for tasks like classification, anomaly detection, and segmentation.

In [153] authors proposed evaluating the potential of HSI techniques, specifically Raman microscopy and Fourier Transform Infrared (FT-IR) microscopy, for analyzing the composition of counterfeit antimalarial tablets. They employed Multivariate Curve Resolution-Alternating Least Square (MCR-ALS) to analyze the hyperspectral data.

In [154] authors used near-infrared HSI to capture the local evolution of these transformations. In [155] authors employed multi-series HSI in combination with Multivariate Curve Resolution – Alternating Least Squares (MCR-ALS) and Parallel Factor Analysis (PARAFAC and PARAFAC2) to monitor solid-state transitions on the surface of pharmaceutical solid dosage forms (SDFs).

In [120] author introduces a rapid hyperspectral anomaly detection (HAD) technique that incorporates a fusion of various features and isolation forest. This method assumes that anomalous pixels are more susceptible to isolation compared to background pixels. It involves extracting spectral, Gabor, extended morphological profile (EMP), and extended multiattribute profile (EMAP) features from hyperspectral images (HSI) and constructing isolation forests for each feature.

In [118] authors focus on target detection in hyperspectral images, which has applications in various fields like defense, search and rescue, and mineral exploration. It evaluates multiple target detection algorithms to identify the best performers for detecting sub-pixel targets from different materials. To achieve this objective, the study evaluated and compared a total of eight signature-based hyperspectral target detection
algorithms, which include the GLRT, ACE, SACE, CEM, MF, AMSD, OSP, and HUD, along with three anomaly detectors: RX, Maxmin, and Diffdet. Among the tested algorithms, three were found to perform well and offer complementary information.

In [54] authors proposed the application of deep neural network models to monitor the vertical distribution of Chlorophyll-a (Chl-a), phycocyanin (PC), and turbidity (Turb) in inland waters using drone-borne hyperspectral imagery, in-situ measurements, and meteorological data. Four advanced data-driven models were tested, with ResNet-18 performing the best with an R2 value of 0.70. Additionally, Gradient-weighted Class Activation Mapping (Grad-CAM) highlighted critical reflectance bands near 490 nm and 620 nm in the hyperspectral image, contributing to the understanding of pigment vertical distributions.

In [230] authors introduce a novel hyperspectral image classification method called SPERW, which stands for SuperPixel-based Extended Random Walker. This method involves three main steps. Initially, a multiscale segmentation algorithm generates superpixels representing homogeneous regions with adaptive shapes and sizes. Then, a weighted graph is constructed based on these superpixels, where nodes represent superpixels and edges indicate similarity. Support vector machines are used to classify individual pixels and approximate prior probabilities for the superpixels. Finally, the Extended Random Walker algorithm optimizes these prior probability maps by considering both spectral stability and spatial correlations among superpixels.

In [229] authors introduce an efficient deep fully convolutional network (FCN) called ENL-FCN for hyperspectral image (HSI) classification. While conventional methods like CNNs excel in learning local spectral-spatial features, ENL-FCN addresses the need to capture long-range contextual information by integrating an efficient nonlocal module. This module operates in a specially designed criss-cross path for computational efficiency. Through recurrent operations, ENL-FCN aggregates pixel responses from the entire HSI. This approach offers three key advantages: effective integration of long-range contextual information, flexibility for embedding the efficient module in deep neural networks, and reduced computational demands. Experimental results on three HSI datasets demonstrate superior classification performance with lower computational costs compared to leading deep neural networks for HSI.

In [228] authors introduce a novel deep learning model called the multi-scale spectral-spatial dual-transformer network (MS3DT) for hyperspectral image (HSI) classification. Unlike convolutional neural networks, the MS3DT leverages transformers to process both spatial and spectral information effectively. It comprises a feature pyramid network (FPN), a spectral transformer subnetwork (SPECT), and a spatial transformer subnetwork (SPAT) to capture multi-scale characteristics and improve representational capacity.

In [231] addresses the challenge of cost-effective hyperspectral data acquisition and processing. It introduces a method called spectral Super-Resolution (SR) applied to Airborne Visible and infrared imaging Spectrometer (AVIRIS) data. This approach involves reconstructing hyperspectral band radiance from a limited set of multi-spectral bands using dictionary learning and further denoising with machine learning, particularly Random Forest Regression. Initially, the radiance values for hyperspectral bands are estimated by analyzing 30 specific input multi-spectral bands. This estimation is achieved through a dictionary created with K-Singular Value Decomposition (K-SVD). Subsequently, a denoising process is applied using Random Forest Regression.

In [232] authors introduce a novel approach called superpixelwise adaptive SSA (SpaSSA) for enhancing hyperspectral image (HSI) feature extraction. Unlike conventional methods, SpaSSA addresses issues like sensitivity to window size and high computational complexity under large windows by adaptively applying singular spectral analysis (SSA) or 2-D singular spectrum analysis (2D-SSA) to each superpixel derived from the HSI. This adaptive approach considers the local spatial information within the image, making it more effective in characterizing objects.

In [233] authors focus on utilizing drones and high-resolution Terrestrial Hyperspectral (THS or HSI) data for crop classification in precision agriculture. It introduces a deep convolutional neural network architecture, comprising six layers, to classify aerial images captured by drones and HSI data. The study combines the ResNets model and architecture with a deep learning network and recurrent neural learning network (RCNN) model to analyze HSI data.

B. Recent Algorithms

Hyperspectral imaging (HSI) algorithms have been evolving rapidly across various domains. In the realm of segmentation, deep learning techniques like Convolutional Neural Networks (CNNs) and recurrent neural networks are being employed to enhance spectral analysis, enabling more accurate identification of materials. Unmixing techniques, such as sparse unmixing and non-negative matrix factorization, have improved material identification in hyperspectral images. Algorithms for anomaly detection are becoming more adept at detecting subtle deviations, making them valuable for security and quality control applications. Dimensionality reduction methods, including autoencoders, help reduce the complexity of hyperspectral data. Additionally, transfer learning is being utilized to leverage pre-trained models for feature extraction, particularly in scenarios with limited data. Lastly, there is a growing emphasis on optimizing algorithms for real-time processing, facilitating faster on-board or near-real-time hyperspectral analysis, which is critical in many applications.

Autoencoders [234][235][236][237][238] in HSI are neural network architectures that learn efficient representations of high-dimensional spectral data. They consist of an encoder, which maps the input hyperspectral data (X) to a lower-dimensional latent space (Z), and a decoder, which reconstructs the data from the latent space. Autoencoders learn to capture essential spectral features in the latent space while reducing data dimensionality, making them useful for various tasks in HSI, including denoising, feature extraction, and anomaly detection.
HSI segmentation [244][245][246][247][248] is a process of partitioning a hyperspectral image into distinct regions or objects based on their spectral properties. It aims to identify and delineate different materials or land cover types within the image, enabling applications like land use classification and target detection in remote sensing.

Real-time processing of HSI [257][258] involves the rapid analysis and interpretation of hyperspectral data as it is acquired, often with minimal delay. It is essential for applications requiring immediate decision-making, such as environmental monitoring, surveillance, and industrial quality control, where timely information extraction is critical for effective actions. Advanced algorithms and optimized hardware are employed to ensure the swift and efficient analysis of hyperspectral data in real time.

Generative Adversarial Networks (GANs) in HSI consist of two neural networks: a generator and a discriminator. The generator generates synthetic hyperspectral images, while the discriminator distinguishes between real and synthetic data. The GAN [239][240][241][242][243] model architecture in HSI typically involves a generator network (G) that generates realistic hyperspectral images from random noise and a discriminator network (D) that tries to differentiate between real and generated data. The G and D networks are trained simultaneously in a competitive manner, with G aiming to produce increasingly realistic spectral data while D tries to improve its ability to distinguish real from fake. This adversarial training process leads to the generation of synthetic hyperspectral images that closely resemble real ones, which can be valuable for data augmentation and generation in applications like image synthesis and anomaly detection.

In [233] authors combine the ResNets model and architecture with a deep learning network and recurrent neural learning network (RCNN) model to analyze HSI data. The CNN model achieved an impressive overall accuracy of 97.16% for drone data, and similar accuracy for cabbage, eggplant, and tomato crops. In [249] authors present a novel methodology for hyperspectral image classification that addresses the challenges posed by high-dimensional data and limited labeled samples. Their approach combines spectral and spatial features by utilizing deep autoencoders to extract relevant information while maintaining data dimensionality. A multi-view deep autoencoder model integrates these features into a joint latent representation space, which is then used to train a semi-supervised graph convolutional network for classification. In [256] author introduces a novel hyperspectral image classification method, Spe-TL, addressing challenges faced by deep learning methods, such as sample dependence and slow training. It utilizes optical flow estimation to capture global spectral variation between contiguous bands. A transfer learning strategy adapts a pre-trained network from video data to hyperspectral feature extraction. The proposed vote strategy enhances classification accuracy, and experiments on four benchmark HSI scenes demonstrate Spe-TL’s competitive performance, especially for scenes with planar ground objects. In [250] authors introduce a novel approach for enhancing the resolution of hyperspectral images by fusing low-resolution hyperspectral images (LR HSI) with high-resolution multispectral images (HR MSI). Unlike existing methods, this approach leverages the complex regional variations in hyperspectral characteristics by employing a mixture of recurrent neural networks (RNNs) within a variational probabilistic framework. It clusters spectral characteristics, uses different RNN experts for various spectral regions, and incorporates a cluster-specific learnable Gaussian prior to account for heterogeneity.

In [234] author proposes the integration of HSI and Autoencoders (AE) as a potent approach for various industries. This combination promises enhanced data analysis, particularly in healthcare and environmental monitoring, by uncovering hidden patterns and enabling more informed decisions. In [235] authors introduced a novel approach called Dual Graph Autoencoder (DGAE) for hyperspectral image (HSI) feature extraction. DGAE leverages both spatial information and spectral band correlations to build dual graphs, enhancing the extraction of discriminative features from HSIs. By constructing superpixel-based similarity graphs and band-based similarity graphs, DGAE captures the geometric structure of HSIs effectively. In [236] author presents a novel hyperspectral target detection method that addresses challenges like intra-class dissimilarity and interclass similarity due to interference from various sources. This method combines an unconstrained linear mixture model with deep learning. It begins by reducing interference using a specially designed deep-learning-based hierarchical denoising autoencoder and then performs accurate detection through a two-step subspace projection for background suppression and target enhancement. Additionally, it introduces an efficient spatial-spectral unified endmember extraction technique. In [237] authors introduced a method, aeDPCN, to enhance the spatial resolution of hyperspectral images while preserving spectral information effectively. In [238] authors introduced an unsupervised approach for hyperspectral image super-resolution, which combines low-resolution HSI with high-resolution multispectral images to create high-resolution HSI (HR-HSI). It employs an implicit autoencoder network, treating each pixel as an individual sample, and integrates nonnegative matrix factorization (NMF) into the network.
In [239] authors proposed a convolutional deep generative adversarial network (DCGAN) for generating synthetic hyperspectral images of epidermal lesions, with a focus on skin cancer diagnosis. In [240] authors proposed a novel approach called the Immune Evolutionary Generative Adversarial Network (HIEGAN) to address the challenges in hyperspectral image classification (HIC) using deep learning, especially with small sample sizes. In [241] authors introduced a novel approach called HyperViTGAN, a semisupervised generative adversarial network with a transformer, designed to address the class imbalance problem in hyperspectral image classification. HyperViTGAN incorporates an external semisupervised classifier to prevent the mislabeling of minority-class samples by the generator. It utilizes skip connections between the generator and discriminator to generate HSI patches through adversarial learning, preserving critical information. In [242] authors proposed a method that combines HSI and deep convolutional generative adversarial networks (DCGAN) to predict the oil content of individual maize kernels rapidly and non-destructively. In [243] authors proposed a novel method, MSRA-G, which combines multi-scale residual attention (MSRA) with Generative Adversarial Networks (GANs) to enhance hyperspectral image (HSI) classification accuracy in scenarios with limited training samples. MSRA-G initially generates synthetic samples to improve separability, addressing the challenge of limited training data. It employs a 3D–2D hybrid network to extract multi-scale context information, with two multi-scale feature extraction modules.

In [244] authors conducted a comprehensive study using HSI data from open surgery on pigs to investigate its effectiveness in semantic organ segmentation. They explored different spatial granularities of the HSI data and compared it with RGB data and processed HSI data. In [245] authors introduced a novel technique called Adaptable Rectangular Convolutions (ARCs) to address challenges in hyperspectral image semantic segmentation using convolutional neural networks (CNNs). In [246] authors present a novel approach called Active Diffusion and VCA-Assisted Image Segmentation (ADVIS) for material discrimination in hyperspectral images. ADVIS selects high-purity, high-density pixels that are distant from others in diffusion space and queries their ground truth labels to propagate to the entire image. In [247] authors introduced a two-branch convolutional neural network called TBN-MERS for hyperspectral image classification, which leverages multi-spectral entropy rate superpixel segmentation (ERS) to enhance spectral–spatial information extraction. TBN-MERS effectively fuses superpixel-scale and neighborhood-scale information, resulting in improved classification accuracy, robustness, and generalization. In [248] authors proposed a novel model called Clustering Ensemble U-Net (CEU-Net) for hyperspectral semantic segmentation. They address the challenge of neighborhood information in complex hyperspectral datasets and compare the performance of CEU-Net with and without preprocessing steps like patching.

In [251] authors introduced a novel hyperspectral unmixing (HU) model, SMRNMF, aimed at improving the accuracy of estimating endmembers and their abundances in hyperspectral images (HSI). Unlike traditional methods that lack consideration of spatial distribution, SMRNMF incorporates subspace clustering and spatial correlation into a sparse non-negative matrix factorization (NMF) framework. This approach leverages local correlations between pixels, utilizes self-expression characteristics of the data, and employs a smoothing matrix to enhance unmixing performance.

In [253] authors introduce TSN-HAD, a transferable network with a Siamese architecture for hyperspectral anomaly detection. TSN-HAD uses similarity metric evaluation to identify anomalies and employs a spectral-angle-based contrastive constraint to enhance feature discriminability. Additionally, it utilizes an unsupervised adaptive clustering method to improve transferability without prior knowledge. In [254] authors present an efficient method for salient object detection in hyperspectral images by combining deep autoencoders with one-class support vector machines (SVMs). It formulates the problem as unsupervised background spectral reconstruction-based anomaly detection. The deep autoencoders model the background of the hyperspectral image, and the one-class SVM detects salient objects based on anomaly detection. In [255] authors introduce a novel approach for salient object detection in hyperspectral images (HSIs) using a convolutional neural network (CNN). It employs an extended morphological profile (EMP) followed by a CNN to simultaneously leverage nearby pixel information and high-level features.

In [252] authors present a novel hyperspectral unmixing (HU) method, SSC-NMF, that overcomes limitations in traditional non-negative matrix factorization (NMF)-based approaches. SSC-NMF incorporates sparse regularization to ensure sparsity of the abundance matrix, Total Variation regularization for smoothness in the abundance map, and piecewise smoothness constraints for end-member signatures in spectral space. Experimental results on synthetic and Cuprite datasets show that SSC-NMF outperforms several state-of-the-art HU methods in terms of Spectral Angle Distance.

In [257] author introduces Hyplex, an innovative HSI system that overcomes the limitations of traditional bulky optical components. Hyplex is CMOS-compatible and uses nanoscale metasurfaces designed through artificial intelligence, eliminating the need for expensive spectrometers. It achieves real-time and high-resolution HSI at a lower cost. The authors compare Hyplex’s performance to existing methods, demonstrating its superiority in spectral reconstruction and semantic segmentation. Additionally, the paper introduces FVgNET, a large labeled hyperspectral dataset for semantic segmentation, contributing to the field of HSI. In [258] authors present a novel approach that combines deep learning (DL) and chemometrics for processing spectral images, even when there are very few samples available. The method divides the task into two parts: DL for object detection and recognition, and chemometrics for predicting chemical properties based on latent space modeling. Transfer learning is applied to adapt a pre-trained YOLOv4 object detection network for spectral images from laboratory settings.

Future algorithm development in HSI is expected to focus on enhancing computational efficiency, enabling real-time analysis, and addressing challenges related to big data. Additionally, there will be a continued exploration of advanced
machine learning techniques, deep learning architectures, and explainable AI methods to extract valuable information from hyperspectral data and improve its applicability across various domains.

III. HYPERSPECTRAL IMAGING APPLICATIONS

A. Earth Sciences, Exploration, and Monitoring

Different research showcases a significant advancement in the field of hyperspectral imaging (HSI) and geological modeling, with practical implications for applications such as mineral exploration and environmental assessments. The rigorous methodology and impressive accuracy achieved in distinguishing rock types using hyperspectral data contribute to the broader understanding and utilization of HSI in geological studies. HSI offers a fast and automated method for mapping geological features, enhancing the documentation and updating of geological models in construction projects [10]. This technology enables several benefits, including: (i) comprehensive mapping of tunnel surfaces, (ii) identification of mineral types that may be challenging to discern visually, and (iii) the creation of a geological archive for post-excavation evaluation and surface sealing [10].

In [9], the authors conducted a comprehensive analysis of a carbonate rock outcrop containing limestone and dolostone using 3D hyperspectral mapping in the SWIR spectrum and a UAV-derived digital elevation model (DEM). Their integrated 3D geological model, combining hyperspectral maps and DEM data, provided detailed information about the rock formations, including attributes like thickness, slope, classification, strike, and dip. The study employed various preprocessing techniques and the Random Forest (RF) algorithm for accurate classification of carbonate rocks, achieving high accuracy levels. Additionally, Binary Logistic Regression (BLR) was used for band selection and the derivation of rock indices, enhancing the generalizability of the results.

In [11], the authors conducted a study to assess the feasibility of using HSI to distinguish ore from waste during excavation in mining operations. They developed a prototype system that combined hyperspectral cameras and LiDAR to capture spatially located hyperspectral data cubes. By creating a reference library of spectra from assayed samples and employing spectral angle mapping (SAM) and convolutional neural network (CNN) classifications, they demonstrated accurate differentiation between ore and waste materials, indicating the potential for excavator-mounted hyperspectral systems to optimize ore extraction and reduce dilution. While both methods had some misclassifications, CNN outperformed SAM in terms of class accuracy and overall accuracy, primarily due to reduced noise in its classification results. In [12], the authors conducted a study using ground-based HSI and terrestrial laser scanning to create mineralogical maps of Late Albian rudist buildups within the Edwards Formation in Texas. These maps offer valuable insights into sedimentological features, depositional environments, diagenetic processes, and hydrocarbon reservoir characterization in areas that are otherwise difficult to access. By accurately distinguishing various facies within the formation and utilizing Digital Outcrop Models (DOMs), this research provides a comprehensive understanding of rudist buildups, enhancing geologic studies and subsurface modeling for hydrocarbon reservoir properties. The hyperspectral images were classified using the spectral Angle Mapper (SAM) image processing algorithm. In [13], the authors conducted a six-month study at the Phoenix mine in Nevada, utilizing visible-near and short-wave infrared (VNIR-SWIR) HSI to analyze samples from different sources. This approach successfully created predictive models for gold-copper recovery, grade, and throughput, showcasing the effectiveness of HSI in optimizing operations affected by complex silicate mineralogy. Various techniques, including multiple linear regression, partial least squares, and deep learning, were employed to construct these predictive models, demonstrating strong correlations with observed data. In [14], authors propose an innovative approach to rapidly detect rare earth elements (REEs) on the Earth’s surface using lightweight drones equipped with hyperspectral sensors. This method offers quick results with low detection limits and has been successfully tested in Namibia and Finland, making it a valuable tool for exploration and monitoring of mining activities. The process involves several crucial steps, including dark current subtraction, radiance value conversion, lens distortion correction, band co-registration, georeferencing,
orthorectification, and spectral correction, resulting in a coherent hyperspectral mosaic for effective REE detection. In [16], the authors have presented a novel toolbox for efficiently processing hyperspectral data collected by Unmanned Aerial Systems (UAS). This toolbox streamlines various correction processes, including co-registration, mosaicking, geo-referencing, and topographic and illumination correction, making drone-borne hyperspectral data highly practical for geological and environmental applications, particularly for mineralogy and soil composition analysis. These corrections improve data quality, even in challenging conditions, making UAS-based hyperspectral surveys a valuable and efficient choice for high-resolution geological investigations. In [17], the author presents an effective method for analyzing erosion-prone coastal cliffs using ground-based VNIR HSI, particularly in challenging-to-reach locations. SVM and MTMF classification techniques were applied to volcanic island data in South Korea, with SVM showing higher accuracy, although challenges arise when classifying rocks primarily based on albedo and dealing with uneven surfaces and stratification. This approach holds promise for monitoring geomorphological changes and safety on volcanic islands, with future improvements expected through the use of SWIR hyperspectral data and integrated LIDAR analysis. In [18], the authors demonstrated a novel application of HSI to study complex diagenetic processes in carbonate rocks, specifically focusing on dolomitization and cementation in the Cathedral Formation. They used spatial-spectral endmember extraction techniques to differentiate various dolomite phases and limestone, allowing them to map spatial distributions and examine variations in dolomite stoichiometry, revealing the potential for more comprehensive geological analyses beyond typical mineral identification. In [19], the authors demonstrated the utility of ground-based HSI for analyzing vertical rock exposures and characterizing lithological variations using Spectral Feature Fitting (SFF) and Mixture-tuned Match Filtering (MTMF) for image classification. Their findings indicate that this approach is effective in mapping lithological units and mineralogical changes in near-vertical rock faces, shedding light on geological processes, while also acknowledging the need for addressing geometric distortions in future research. In [20], the authors demonstrated the effectiveness of various feature extraction (FE) algorithms in geological HSI, emphasizing their utility in differentiating mineral domains based on spatial and spectral differences. Innovative FE methods like WSRRR and OTVCA outperformed conventional techniques such as PCA and MNF, highlighting the potential for advanced FE algorithms in mineral mapping for geoscience and mineral exploration.

In [21], the authors propose the potential of hyperspectral remote sensing in geoscientific research, with a focus on mining-related applications. They highlight the advantages of both airborne and spaceborne hyperspectral data and successfully demonstrate its use for mapping mineralogy and proxy minerals related to ore mineralization, emphasizing the need for high spatial resolution data for detailed mapping within mineralization zones. In [22], the authors studied the potential of GF-5 AHSI satellite imagery for lithological mapping using deep learning methods, comparing them to traditional support vector machine approaches. They found that all methods achieved over 90% accuracy, with M3D-DCNN being the most accurate and stable choice, and recommended the use of GF-5 AHSI imagery, particularly its SWIR bands, for lithological mapping based on hyperspectral data. In [23], the authors explored the use of advanced hyperspectral satellite data, including DESIS and PRISMA, for geological interpretation and evaluated three feature extraction algorithms for lithological mapping in India. Their study showed that feature extraction algorithms, especially PCA, enhanced geological mapping using hyperspectral data, emphasizing the potential of advanced hyperspectral datasets for accurate mineral mapping in the region. They recommend employing these datasets with advanced feature extraction methods for improved geological interpretation and mineral mapping. In [24], the authors proposed HESSC, a novel hierarchical sparse subspace-based clustering algorithm for HSI data. HESSC overcomes computational challenges, predefined cluster numbers, and achieves autonomous cluster number determination, making it an effective tool for hyperspectral image analysis, as demonstrated through experiments with real datasets. In [25], the authors discuss the importance of Surface Biology and Geology (SBG) as a "Designated Targeted Observable" (DO) and the establishment of an SBG Algorithms Working Group. This group aims to develop algorithms for hyperspectral and multispectral measurements to address SBG DO priorities, drawing insights from numerous scientists and research in the field. In [26], the paper emphasizes the use of machine learning and advanced image analysis in geology to improve the process of petrographic description. It highlights two applications: one that classifies rock properties using various machine learning algorithms and another that predicts Dunham textures from carbonate thin sections using convolutional neural networks, demonstrating the potential of these techniques to enhance geoscience applications and expand imaging capabilities in the field. In [27], the authors present a novel approach called Robust Supervised ISOMAP for hyperspectral image classification, addressing the challenge of nonlinear data in hyperspectral remote sensing. By incorporating credibility and class information into manifold distance calculation, this method improves classification accuracy and anti-noise performance without adding significant computational overhead, making it an effective technique for hyperspectral image analysis. In [28], the authors present methods for detecting and mapping hydrocarbons in continental areas using hyperspectral remote sensing data, overcoming challenges related to small-scale occurrences and spectral overlap with minerals. A prediction model for PHC concentrations in soils was developed based on field experiments and spectral measurements, indicating the potential utility of hyperspectral data for oil industry exploration and environmental monitoring. In [29], the authors demonstrate the application of SASI aerial hyperspectral data to extract information about clay alteration minerals in the Jimusar Area, Xinjiang Province, China, with relevance to oil and gas exploration. The study involves data processing steps like calibration, spectral reconstruction, noise separation, and automatic recognition using the PPI and MTMF methods, providing a valuable method for mineral alteration mapping.
in the context of oil and gas exploration using hyperspectral remote sensing. In [30], the authors address the critical issue of detection limits in hyperspectral remote sensing for petroleum hydrocarbon contamination in soils. It highlights that the detection limit is affected by spatial factors and soil type, providing essential insights into the applicability and constraints of hyperspectral remote sensing for assessing petroleum hydrocarbon contamination in different environmental scenarios.

In [31], the authors explore the significant impact of unmanned aerial vehicles (UAVs) or drones in the petroleum industry, offering a comprehensive overview of their applications in various sectors. It identifies key areas such as oil spill detection, pipeline monitoring, and environmental assessment where drone technology can revolutionize data collection, emphasizing the potential for transformative advancements in the petroleum sector. In [32], the authors focus on advanced techniques for detecting petroleum hydrocarbon (PHC) contamination in latosols, emphasizing the environmental implications of oil and gas activities. It utilizes diffuse reflectance spectroscopy and HSI, achieving a 98% accuracy rate in classifying contaminated soils using the Multiple Endmember Spectral Mixture Analysis (MESMA) method. These methods prove effective in identifying and characterizing PHC contamination, providing valuable support for environmental remediation and protection efforts. In [33], the authors explore the early detection of onshore natural oil seepages and accidental leaks, emphasizing their significance for subsurface reservoir identification and the oil industry. It utilizes HSI and wavelet processing to create a spectral library that can separate different phases in soil-hydrocarbon mixtures, enabling the identification of hydrocarbon type and concentration. In [34], the authors explore the use of airborne hyperspectral sensors to detect methane emissions from geological reservoirs, pipelines, and petroleum facilities. It conducted a field experiment and applied advanced algorithms to process thermal infrared data, effectively identifying methane signatures and mapping gas plumes, showcasing the technology’s potential for the petroleum industry and environmental management. In [35], the authors investigate the application of portable Near Infrared spectroscopy (NIRS) and NIR-Hyperspectral Imaging (NIR-HSI) for assessing oil content and fatty acid composition in Brassica seeds. The study employs chemometric techniques like PCA, PLSR, and PLS-DA to distinguish between Brassica species, achieving accurate classification. Both NIRS and NIR-HSI show promise for quantifying oil content and composition in Brassica seeds, serving various industrial and consumer purposes, with NIR-HSI offering advantages in some aspects. In [36], the authors present a compact fluorescence hyperspectral system designed for rapid analysis of oil spill incidents, capable of identifying different types of crude oil, mapping their distribution, and estimating oil film thickness. The system utilizes an in-house fabricated imaging spectrometer with high spectral resolution and demonstrated effective oil type analysis, distribution mapping, and thickness estimation. While it shows promise for field analysis of oil spills, potential limitations related to excitation and interference from seawater components should be considered in real-world applications. In [37], the authors investigate the application of reflectance spectroscopy for the direct detection and monitoring of petroleum hydrocarbon (PHC) leaks in exposed soils near petroleum facilities. Laboratory experiments with controlled PHC contamination reveal distinct spectral characteristics, temporal patterns, and detection limits in the visible-near infrared and short-wave infrared wavelengths, showcasing the potential of this method for environmental monitoring and management of PHC pollution.

In [38], the authors discuss the development and architecture of HSI systems and processing pipelines for a collaborative ocean observation project involving satellites and unmanned aerial vehicles (UAVs). It highlights the completion of the HYPSO-1 satellite’s hyperspectral image processing pipeline and ongoing efforts to design versatile and user-friendly UAV-based systems for HSI, emphasizing the importance of computational capacity as UAVs become more autonomous. In [39], the authors discuss the AEROS CubeSat, designed for ocean observation over the Portuguese Atlantic region. It highlights the CubeSat’s high-resolution Hyperspectral Imager (HSI) and Software Defined Radio (SDR) capabilities, which enable the collection of oceanographic and meteorological data for various applications, including fisheries management, ecosystem-based management, and marine protection. In [40], the authors present a deep learning approach using an 8-layer fully-connected neural network to classify coastal wetlands based on CHRIS hyperspectral imagery, incorporating spectral and texture features. The results demonstrate that this DCNN model achieves high classification accuracy (99%) and outperforms other methods, particularly improving the accuracy of tidal flat and farmland classification in coastal wetlands.

In [41], the authors present an innovative approach to underwater hyperspectral imaging (UHI) for seafloor characterization using a stationary platform on the seabed. The UHI data successfully identified 24 spectrally distinct seafloor materials in a hydrothermal field study, showcasing the potential of this method for high-resolution seafloor exploration in deep-sea mining areas and environmental assessments. In [42], the paper introduces a novel approach to hyperspectral image classification for coastal wetlands, utilizing a multi-object convolutional neural network (CNN) decision fusion technique. This method effectively addresses spectral aliasing and class mixing challenges, outperforming other methods with an overall accuracy of 82.11% and demonstrating its value in classifying complex coastal wetland scenarios. In [43], the authors present a novel hyperspectral image classification approach that leverages a spectral sequence-based nonlocal long short-term memory (LSTM) network. This method effectively utilizes spectral information and contextual features, resulting in superior pixel-level classification accuracy compared to existing methods, as demonstrated through experiments on multiple datasets. In [44], the authors evaluate the potential of an underwater hyperspectral imager (UHI) system for mapping and monitoring benthic habitats in the Mediterranean Sea. Despite technical challenges, the study demonstrates the UHI camera’s suitability for habitat mapping and seabed monitoring, with quantifiable and repeatable classifications achieved using the spectral angle mapper (SAM).
supervised classification method, offering valuable insights for marine habitat research and European MSFD indicators. In [45], the authors evaluate the performance of a cost-effective hyperspectral transmissometer called VIPER, which emulates the visible light spectrum using LEDs. While the study identifies issues related to thermal management and ambient light contamination, it concludes that VIPER provides reliable beam attenuation measurements in coastal waters, offering a valuable alternative for specific applications in these environments compared to traditional transmissometers. In [46], the authors explore the utilization of a hyperspectral camera, originally designed for satellite and airborne remote sensing, in underwater environments of the Mediterranean Sea. It reveals the potential applications of this adapted technology for mapping and monitoring benthic habitats, making it a valuable tool for marine habitat research and monitoring in underwater settings. In [47], the authors have introduced an innovative methodology for exploring the complex ternary phase space in organic solar cells efficiently. By creating extensive libraries of cells with diverse compositions and thicknesses, they used HSI to analyze these libraries, revealing multiple performance maxima and deviating from conventional donor-to-acceptor ratios, highlighting the utility of high-throughput evaluation and the potential for applying data science techniques in solar cell development. In [48], the authors explore the application of HSI technology and machine learning to characterize space objects and determine their attitude motion. Through simulations and laboratory tests, the study demonstrates the feasibility of extracting surface composition information and tracking object motion using spectral data, offering a promising solution for more accurate tracking of space objects. In [49], the authors provide an extensive overview of the advancements in miniaturized and cost-effective HSI systems, highlighting their integration into various environmental monitoring applications. The article underscores the potential for these devices to become standalone monitoring tools, with growing applications even in extreme environments, and predicts that smartphones equipped with HSI capabilities will play a significant role in environmental science. This reflects a trend toward broader adoption and increased applicability of HSI technology in the environmental monitoring field. In [50], the authors present the ANR HYEP project, which aims to leverage second-generation hyperspectral spaceborne missions to improve urban area observation. The project’s focus is on addressing the challenges posed by urban dynamics, spatial heterogeneity, and the need for detailed land surface property information in urban areas, with applications including assessing vegetation, sealed areas, impervious surfaces, and solar panel coverage.

In [51], the authors have introduced the HyperDiver system, a technology that efficiently collects diverse data in shallow marine ecosystems, including hyperspectral imagery, topographic profiles, irradiance, and water chemistry. By applying machine learning to this data, they demonstrate the creation of high-resolution and accurate maps of benthic habitats, offering a fast, objective, and cost-effective approach for reef monitoring with significant applications in coastal management and ecology. This system combines the benefits of field surveys and remote sensing techniques to enhance reef monitoring capabilities. In [52], the authors introduce an affordable HSI solution with high-resolution capabilities for detecting spectral variations in mm-scale targets. Unlike existing expensive setups, this instrument provides detailed hyperspectral images, particularly useful in mineralogy-based environmental monitoring applications, where it enhances data quality and accuracy without the typical cost constraints. This innovation aims to make high-resolution HSI more accessible, promoting its broader use and democratization. In [53], the authors utilize radiative transfer models and ecological criteria to estimate leaf and canopy nitrogen content in a temperate forest using airborne hyperspectral imagery. By coupling PROSPECT-5 and INFORM models and employing inversion techniques, the study successfully retrieved nitrogen content, with canopy nitrogen estimation accuracy surpassing that of leaf nitrogen. This research advances the mapping of foliar nitrogen, considering both direct and indirect nitrogen effects on canopy reflectance, and aligns with ecological knowledge. In [54], the authors propose the use of deep neural network models to monitor the vertical distribution of Chlorophyll-a (Chl-a), phycocyanin (PC), and turbidity (Turb) in inland waters using drone-borne hyperspectral imagery, in-situ measurements, and meteorological data. Among the tested models, ResNet-18 performed the best, achieving an R2 value of 0.70, and the use of Gradient-weighted Class Activation Mapping (Grad-CAM) identified critical reflectance bands contributing to the understanding of pigment vertical distributions, demonstrating the potential of explainable deep learning for estimating and interpreting pigment profiles in water bodies. In [55], the authors investigate the degradation of untreated wooden surfaces due to weather exposure and UV radiation using HSI in the near-infrared range. The study collected hyperspectral data over time and developed reliable prediction models for degradation by incorporating UV solar radiation, marking a step towards creating a comprehensive weather dose model for assessing wooden surface degradation. In [56], the authors discuss the importance of effective forest characterization and monitoring and explores the integration of HSI and LiDAR data to enhance these processes. It provides a comprehensive review of methods for data fusion categorized into three levels, offering insights into the approaches used in combining hyperspectral and LiDAR data for forest characterization and monitoring, which can advance the field of forest management. In [57], the authors address the need for effective monitoring of benthic habitats in shallow coastal waters and utilizes a variety of remote sensing data, including hyperspectral imagery, to map these habitats accurately. It compares different classification algorithms and finds that Support Vector Machine (SVM) performs best in terms of accuracy, especially when using hyperspectral data, although Maximum Likelihood (ML) demonstrates robustness across various information types and bands. In [58], the authors propose a method for estimating leaf pigment contents and the leaf area index (LAI) in tree-grass ecosystems with low canopy cover using hyperspectral imagery. They demonstrated the consistency of their estimations over two years and found that the approach is valid for monitoring woodland savannas.
and similar sparse forests. In [59], the study presents an automated approach for classifying and mapping tree species in a mixed-conifer forest using high-resolution hyperspectral imagery and a convolutional neural network (CNN) classifier. This approach has significant potential for forest ecosystem monitoring and management, particularly in assessing factors like drought and pests, and the authors have shared their code for similar applications. In [60], the study investigates the use of HSI and vegetation indices (VIs) to distinguish between different woody plant species, specifically Populus tremula, P. alba, and P. simonii. Through various analyses, including ANOVA, Principal Component Analysis (PCA), Decision Tree (DT), and Random Forest (RF) methods, the research consistently identified these species using key VIs like Double Peak Index (DPI), Derivative index 1 (D1), Datt index 3 (Datt3), and Vogelmann index (Vogelmann), offering the potential for using spectral sensors to monitor and assess climate change’s impact on these species’ ranges. In [61], the authors present an innovative and cost-effective method for monitoring the health of peatland habitats, essential for climate change mitigation. Instead of traditional invasive methods, the authors propose using low-cost HSI techniques to monitor the spectral response of Sphagnum plants, serving as proxies for peat health. They employ portable hyperspectral imagers, including a High-Resolution Hyperspectral Imager and an ultra-low-cost Hyperspectral Smartphone, demonstrating their effectiveness in detecting early spectral changes and enabling timely mitigation and restoration efforts. This research underscores the potential of low-cost spectral imaging in peatland health monitoring, making it accessible and efficient for environmental applications and emphasizing its role in providing early warnings for ecosystem preservation.

B. Agriculture and Food Quality and Safety

In the last two decades, hyperspectral imaging (HSI) has emerged as a valuable technology for assessing the quality and safety of horticultural products. This technology, originally from remote sensing, combines machine vision and point spectroscopy to enhance defect detection, contamination identification, and chemical composition mapping. Recent advancements in instrumentation and data analysis have transformed HSI into a nondestructive inspection tool with a wide range of applications in postharvest quality and safety assessment.

In [188], the authors discuss the utility of HSI for monitoring and controlling food processing to ensure product quality and safety. It covers various food processes and highlights HSI’s ability to assess quality parameters. The review concludes that HSI effectively inspects and monitors food manufacturing processes, with potential for enhancing food quality and safety in the future, despite some remaining challenges. In [189], the authors discuss the need for safe and nutritionally beneficial food products and highlights HSI as a nondestructive analysis method for quality and safety assessment. It compiles studies on various food products, emphasizing the potential of HSI to meet the modern food industry’s requirements. In [190], the authors explore different imaging modes and their advantages and disadvantages in HSI. It focuses on applications in assessing the quality, defects, and safety of horticultural products. The article also discusses data processing and analysis methods and concludes by highlighting future challenges and opportunities in this field. In [191], the authors discuss the utility of HSI in evaluating the quality and safety of agricultural and food products, with a focus on fruits and vegetables. It covers the principles, components, image processing, and spectral treatment in HSI. The applications include textural analysis, biochemical component detection, and safety assessment. The paper also addresses technical challenges and future directions for HSI in this context. In [192], the authors discuss the potential of NIR HSI in nondestructive assessment of grain quality and safety. This technology can identify chemical components and their distribution within cereal samples, offering automation and efficiency in the cereal industry. The review covers the theory, principles, and applications of NIR HSI in cereal science. In [193], the authors discuss the use of HSI for analyzing food samples, emphasizing its potential for detailed molecular-level analysis. It outlines the challenges of working with complex food samples and the importance of spectral preprocessing and chemometric techniques for extracting meaningful information. HSI is presented as an advanced tool for quality assessment in the food and agricultural industry. In [194], the authors discuss the rapid evolution of line-scan HSI in the food and agriculture sector over the past 15 years. It covers various principles, systems, and their applications in food inspection, emphasizing the increasing availability of integrated systems for food safety and quality. Advances in hardware and data analysis are expected to drive further progress. In [195], the paper highlights the extensive use of HSI in agriculture and horticulture over the past two decades. It discusses its applications in quality assessment, defect detection, and monitoring, emphasizing its contribution to precision agriculture and sustainability goals in the industry. In [196], the chapter discusses the increasing importance of precision agriculture in modern farming. It focuses on the use of HSI and multispectral imaging (MSI) for crop health monitoring, water assessment, and contaminant detection. The chapter reviews the scientific literature on these applications, including satellite and aerial image acquisition, and discusses their advantages and limitations in precision agriculture. In [197], the authors assess the stability of solar-induced chlorophyll fluorescence (SIF) as an indicator of photosynthesis in a citrus crop canopy over two years. Hyperspectral imagery and the Fraunhofer Line Depth (FLD) method for SIF quantification were used. SIF (FLD3) showed strong correlation with assimilation rates, outperforming other indices. Normalizing SIF FLD3 with control trees established a reliable relationship with assimilation rates, demonstrating its potential in precision agriculture and crop monitoring. In [198], the chapter explores the recent progress in remote sensing, focusing on hyperspectral sensors for precision agriculture. Hyperspectral remote sensing (HRS) is favored over multispectral methods for its detailed spectral information. It discusses HRS sensors and the issues with satellite-based agriculture monitoring, concluding with research challenges and future directions in agricultural studies using hyperspectral data.
In [199], the research assessed the use of solar-induced chlorophyll fluorescence (SIF) from hyperspectral imagery to measure nitrogen levels in semi-arid conditions for precision agriculture. Models incorporating SIF data outperformed traditional indices, indicating the potential of SIF as a valuable indicator for nitrogen assessment in such environments. In [200], the authors investigate the use of hyperspectral imagery and specific spectral indices to quantify water absorption variations in lettuce leaves. The study finds that these indices are related to water content per unit leaf area and are strongly correlated with water content in green parts of leaves but not in stem water content. Spatial resolution of hyperspectral imagery is emphasized as a crucial factor in accurate quantification of leaf water content. In [201], the study evaluated the potential of high-resolution hyperspectral airborne imagery for assessing within-field variability of durum wheat grain yield and grain protein content. It employed narrow-band physiological spectral indices and multi-temporal spectral analysis to predict grain protein content accurately. While the protein content prediction had relatively high overall error, it was comparable to similar studies. The research offers insights into using remote sensing for nitrogen management and selective harvesting, with potential for future exploration of protein content variation at different scales and using different sensing platforms. In [202], the authors investigate the use of remote sensing technology for the detection and management of crop diseases, particularly in precision agriculture. It focuses on the utilization of airborne and satellite imagery during growing seasons for early disease detection and within-season management. The paper highlights variable rate technology for site-specific fungicide application, using the example of cotton root rot in cotton fields. This approach, which involves prescription maps derived from imagery, improves disease control and serves as a valuable resource for researchers, growers, and agricultural professionals interested in employing remote sensing for effective crop disease management. In [203], the authors suggest integrating HSI (VNIR and SWIR) with machine learning to detect the Tomato Spotted Wilt Virus (TSWV) in capsicum plants, supporting precision agriculture. It extracts features from spectral data, such as full spectrum, vegetation indices, and probabilistic topic models, to train classifiers for identifying healthy and infected plant leaves. The results highlight the effectiveness of this approach, especially with full spectrum data, and improved classification with higher-dimensional feature sets. This method has the potential for early disease detection and site-specific intervention, aligning with precision agriculture goals. In [204], the authors underscore the importance of early and accurate plant disease detection in crop production. It explores various optical techniques, including RGB imaging, multispectral sensors, thermography, chlorophyll fluorescence, and 3D scanning, all showing potential in automated disease identification. These methods, whether used up close or from a distance, enable monitoring at multiple scales in plants and fields. The application of advanced data analysis techniques enhances the precision and reliability of disease detection, providing valuable insights into the complex interactions between plants and pathogens. These sensor-based approaches, being nondestructive, complement visual and molecular methods in assessing plant diseases, with significant implications for precision agriculture and plant phenotyping. In [205], the authors present the HyTI (Hyperspectral Thermal Imager) mission, supported by NASA’s Earth Science Technology Office. Its objective is to demonstrate the collection of high-resolution long-wave infrared image data from a compact 6U CubeSat platform. The mission utilizes an inventive interferometric imaging method to generate calibrated image data with multiple spectral channels. In [206], the authors explore UAV-based imaging missions carried out over rice and corn fields in the Philippines, particularly in Isabela province. Spectral reflectance sensors were employed for ground truthing, and aerial imagery was captured using RGB and NIR-retrofitted cameras. These missions were conducted to supply high-resolution imagery for mixed cropping regimes and plots managed by various farmers with different planting dates. The incorporation of UAV imagery offers the potential to improve the efficiency of local government units’ ledger-based monitoring systems used for regional agriculture management. In [207], the study presents a rapid and non-destructive method for assessing and mapping nitrogen levels in apple trees, both at the leaf and canopy levels. It utilized HSI with the ImSpector V10 system and measured nitrogen content in apple leaves. Models for nitrogen estimation were established using raw reflectance and first derivative reflectance. Both Partial Least Squares (PLS) and Multiple Linear Regression (MLR) models showed reasonable predictive accuracy. Notably, the MLR model based on raw reflectance, utilizing only 4 key wavelengths, outperformed other models. This method has the potential to enhance precision nitrogen management in apple orchards. In [208], the authors provide a thorough overview of the use of HSI and deep learning in agriculture. It highlights HSI as a fast, non-destructive technology for capturing spectral data in agriculture. The integration of deep learning techniques has improved hyperspectral image analysis by considering both spatial and spectral information. The review encompasses applications like predicting ripeness, classifying products, and detecting diseases. It also discusses recent advancements in deep learning models and feature networks for hyperspectral image analysis. The paper concludes by addressing current challenges and proposing future research directions in this.
area. In [209], the authors review the utilization of HSI and advanced machine learning algorithms in agriculture, emphasizing the importance of precision agriculture in addressing global population needs. It discusses the use of datasets like Hyperion, Landsat-8, and Sentinel 2 in agricultural applications. Commonly used machine learning methods include support vector machines and random forests, with Convolutional Neural Networks excelling in crop classification with hyperspectral data. This review offers essential insights and datasets for researchers in the hyperspectral remote sensing and machine learning fields related to agriculture.

In [210], the authors investigate various Convolutional Neural Network (CNN) setups for hyperspectral image classification in agriculture. It evaluates four CNN models, including 1D-CNN with spectral data, 1D-CNN with selected bands, 1D-CNN with spectral-spatial features, and 2D-CNN with principal components, using HSIs from Salinas Valley and Indian Pines. The study identifies that 1D-CNN with augmented input vectors, combining spectral and spatial information, achieves the highest accuracy. It also notes that incorporating principal components from neighboring pixels enhances classification accuracy, underlining the importance of both spectral and spatial data in HSI analysis. In [211], the authors discuss the challenges of preprocessing hyperspectral images, focusing on the removal of artifacts and noise while extracting valuable information. It addresses issues like uneven illumination, background noise, and specular reflections in hyperspectral images, emphasizing the role of preprocessing in improving the accuracy of subsequent analysis tasks, including detection, classification, and prediction. The paper also highlights the potential for post-processing to enhance classification results and create spatial distribution maps of chemical components in non-homogeneous samples. In [212], the authors investigate the use of hyperspectral remote sensing data to identify and predict different crop varieties, including Red medlar, jujube, watermelons, and grapes. It applies multivariate analysis methods to select optimal spectral bands for crop discrimination and finds that these bands effectively distinguish between the crop types, with the CARS method performing the best. The study also employs a CARS-PLS-DA model for crop prediction, achieving high accuracy in predicting various crop varieties. This research confirms the potential of HSI for crop identification and prediction, particularly for grape and watermelon varieties. In [213], the study investigates the use of airborne HSI to estimate heavy metal concentrations in agricultural soils, specifically chromium (Cr), copper (Cu), and lead (Pb). Spectral unmixing was applied to improve accuracy by obtaining pure soil spectra. Different models, including random forest (RF), were tested, and RF outperformed others, achieving the best accuracy for estimating heavy metal concentrations in the soil. This research demonstrates the effectiveness of HSI in this application. In [214], the authors examine the potential of HSI for detecting microbial contaminants in agricultural and food products. This technology combines spectroscopy and digital imaging to provide both spectral and spatial data, offering a faster and non-destructive approach compared to traditional methods. While HSI has advantages, challenges such as accurate reference measurements and system development need addressing. The review highlights its potential in microbial evaluation in the agriculture and food industry, suggesting that further research and optical advancements could lead to efficient multispectral imaging systems for online use. In [215], the authors investigated the use of UAV-based HSI data to estimate soil moisture content (SMC) in arid regions. They tested four estimation strategies with the XGBoost algorithm, and strategy IV, combining the fractional-order derivative (FOD) technique and optimal multiband indices, produced the most accurate SMC estimates. The research demonstrates a promising data mining approach for UAV-based hyperspectral data, emphasizing the effectiveness of the FOD technique, especially with the 0.4 order, for improving SMC estimation. This has implications for precision farming and agricultural informatization in arid regions, utilizing remote sensing technology. In [216], the authors introduce a novel crop classification method that optimizes a vegetation feature band set (FBS) and utilizes object-oriented classification (OOC). The enhanced FBS includes 20 spectral indices sensitive to vegetation parameters, improving class separability while reducing data redundancy. OOC further reduces noise, resulting in high classification accuracy. This approach significantly improves crop classification accuracy and has applications in precision agriculture and invasive species monitoring. In [217], the authors discuss the supervised classification of HSI data for identifying wheat-growing areas in Al-Kharj, Saudi Arabia. It utilizes the Parallelepiped and Spectral Angle Mapper (SAM) algorithms within ENVI software. SAM outperforms Parallelepiped. This study highlights the effectiveness of SAM and Parallelepiped classifiers, with SAM’s spectral signature-based approach proving more efficient in wheat area classification. In [218], the authors present a non-invasive automated grading system for banana tiers, assessing quality and size using RGB, HSI and deep learning. This research demonstrates the benefits of combining RGB and HSI in agriculture, with potential applications in sorting various fruits. Future work could expand the scope to include data augmentation, more fruit types, advanced camera systems, and integration with robotics for large-scale fruit classification. In [219], the study investigated the use of unmanned aerial systems (UAS) and hyperspectral imaging to identify mosaic virus infection in sugarcane plants. It characterized the spectral responses of healthy and infected sugarcane to select optimal spectral bands for imaging. Aerial surveys were conducted, and spectral data were processed using the empirical line approach. The classification method, based on spectral information divergence, accurately detected mosaic-infected areas in sugarcane with high precision, illustrating the effectiveness of this approach for disease detection in agriculture. In [220], the authors emphasize the significance of precise plant disease detection for sustainable crop production and discusses the potential of hyperspectral imaging for early disease identification and quantification. The study showcases the successful application of this method in investigating diseases in crops such as barley, wheat, and sugar beet, offering valuable insights into disease mechanisms and plant defenses. Hyperspectral imaging holds promise for applications in precision agriculture, plant breeding, and fungicide screening.
In [221], the study focuses on predicting alfalfa yield using hyperspectral imagery from UAVs, with the aim of benefiting precision agriculture. An ensemble machine learning model that combines multiple algorithms outperforms individual models, achieving a high coefficient of determination (R2) of 0.874 when using selected features. The research demonstrates the model’s adaptability to different machinery compaction treatments and emphasizes the effectiveness of hyperspectral imagery in predicting alfalfa yield, suggesting potential enhancements through the incorporation of environmental factors in future studies. In [222], the authors discuss the potential of utilizing Big data, machine learning, and deep learning in agricultural remote sensing, particularly with hyperspectral and multispectral data. It reviews research in this area, highlights applications, and introduces ensemble machine learning and scalable parallel discriminant analysis to tackle challenges. Experimental results confirm the approach’s effectiveness. The conclusion underscores the need for efficient algorithms, computational architectures, standardization, and data management to fully utilize Big data and hyperspectral information in agriculture. Future work intends to enhance and expand the proposed framework to address these challenges. In [223], the authors explore the use of hyperspectral imaging and convolutional neural networks (CNNs) to detect and predict the vitality of maize seeds, providing an efficient alternative to traditional methods. Various models were built, with the 2DCNN model achieving the highest recognition accuracy of 99.96% based on image data. The combination of spectral and image data offers a promising framework for seed germination research. In [224], the study employs non-destructive spectral image analysis, utilizing a convolutional neural network (CNN) model, to assess cold damage in corn seedlings. Hyperspectral images of different corn varieties subjected to cold treatment were processed for CNN modeling. The CNN model effectively detected cold damage levels in various corn varieties and exhibited a strong correlation (0.8219) with chemical analysis results. This research underscores the utility of CNN-based spectral analysis for evaluating cold damage in corn seedlings, facilitating the selection of cold-stress-resistant crop varieties. In [225], the authors outline a methodology for precise estimation of soil moisture content (SMC) in arid regions using UAV hyperspectral data. It combines optimal spectral indices and ground observations in a machine learning framework to achieve highly accurate SMC predictions. The study compared two machine learning algorithms, random forest (RF) and extreme learning machine (ELM), with RF showing superior performance. This approach has significant potential for enhancing agroecosystem management and conservation strategies in arid regions through precise SMC monitoring. In [226], the paper focuses on high-precision mapping of soil organic carbon (SOC) stocks in low-relief agricultural regions. Traditional covariates for soil mapping are insufficient for capturing SOC spatial variations. The study uses time-series multispectral remote sensing images and employs partial least square regression (PLSR) and extreme learning machine (ELM) models to predict SOC stock, SOC, and soil bulk density (SBD). ELM outperforms PLSR, and combining Sentinel 2 images with ELM results in the best predictions. The study effectively demonstrates the use of time-series multispectral remote sensing for mapping soil properties in low-relief farmland, offering valuable insights for agricultural management and understanding the carbon cycle. In [227], the authors investigate the use of hyperspectral imaging to detect both root-knot nematode infestation (biotic stress) and water deficiency (abiotic stress) in tomato plants, which exhibit similar symptoms under these stresses. They used partial least squares – support vector machine (PLS-SVM) classification and achieved high accuracy (up to 100%) in distinguishing well-watered from water-deficient plants and identifying nematode-infested plants (90-100% accuracy). The study emphasizes the importance of shortwave infrared spectral regions in assessing nematode infestation severity. Overall, hyperspectral imaging is effective in differentiating between biotic and abiotic stresses in plants.

C. Healthcare, Pharmaceuticals and Medical Imaging

Hyperspectral imaging (HSI) holds significant promise in healthcare, pharmaceuticals, and medical imaging applications. It enables precise tissue characterization, aiding in the early detection of diseases such as cancer, as well as the assessment of tissue viability during surgeries. In pharmaceuticals, HSI assists in quality control by analyzing the chemical composition of drugs and ensuring uniformity. Moreover, it plays a vital role in non-invasive medical imaging, providing detailed information about tissue physiology and aiding in diagnostics and treatment planning.

In [147], the authors suggest employing HSI technology for pharmaceutical visual inspection to improve quality control. Traditional RGB sensor-based methods have limitations. This paper explores the applications of HSI in pharmaceutical contexts, encompassing areas such as counterfeit drug detection, analysis of active tablet components, and quality assessment of herbal medicines and medical materials. It delves into the technology and hardware, including Raman spectroscopy, related to HSI. The paper underscores the emerging trend of using HSI-based robots for pharmaceutical quality inspection, highlighting the field’s potential and future developments. In [148], the authors emphasize the increasing significance of imaging, especially HSI in contemporary drug development. This technology provides a profound understanding of intricate pharmaceutical products, both in controlled laboratory settings and real-time process analytical situations. It allows for the examination of component distribution across different spectral ranges such as infrared, near-infrared, Raman, ultraviolet, and RGB imaging. Regulatory authorities acknowledge these tools, and they are progressively incorporated into the drug development process. The paper envisions HSI as a central element of continuously operating production systems in the future, underscoring its role in pharmaceutical development and quality control. In [149], the authors emphasize the increasing significance of imaging in modern drug development, particularly in the context of in-line prediction of active pharmaceutical ingredients (APIs) in microtablets using HSI. This study covers various API concentrations and employs visible/near-infrared (vis/NIR) and short-wave infrared (SWIR) regions.
Two multivariate data modeling methods, partial least-squares regression (PLSR) and principle component regression (PCR), are compared against a reference high-performance liquid chromatography (HPLC) method. Notably, PLSR models, especially in the SWIR region, exhibit reliable performance with a high coefficient of determination (R²) of 0.96. The research suggests that HSI, when combined with multivariate data analysis and chemical imaging, has the potential to enhance the rapid in-line determination of pharmaceutical product quality in production settings. In [150], the authors developed a UV HSI prototype for characterizing active pharmaceutical ingredients (API) in tablets, specifically ibuprofen, acetylsalicylic acid, and paracetamol. The study involved two sample sets: one with 100% API content and another with commercially available painkiller tablets. Reference measurements were conducted on pure APIs in liquid solutions and solid phases using a commercial UV spectrometer. Principal component analysis (PCA) was applied to differentiate the hyperspectral data, and the first two components effectively separated all samples. The prototype’s robust design suggests potential for large-scale industrial applications, offering high spatial/spectral resolution and rapid data acquisition, making it suitable for scientific studies. In [151], the authors used Raman hyperspectral images and multivariate curve resolution-alternating least squares (MCR-ALS) to analyze the distribution of active and excipient components in a pharmaceutical drug product, with a focus on a low-dose constituent. Various data analysis approaches were compared, including filtered and non-filtered data and an augmented dataset with appended low-dose component information. The study found that using an augmented dataset allowed for the correct recovery of the distribution of all components in the drug product. In [152], the authors introduced a method utilizing near-infrared hyperspectral imaging (NIR-HSI) to simultaneously quantify the active pharmaceutical ingredient (API) content and coating amount on tablet surfaces during pharmaceutical manufacturing. The process achieved high accuracy and practical applicability for real-time quality control in pharmaceutical production. In [153], the authors proposed assessing HSI techniques, specifically Raman microscopy and Fourier Transform Infrared (FT-IR) microscopy, for analyzing counterfeit antimalarial tablets. Results showed Raman HSI’s effectiveness in detecting low-dose compounds and identifying counterfeit samples from different brands. This highlights its value in counterfeit pharmaceutical product identification. In [154], the authors proposed a study on solid-state transformations in tablets containing piroxicam monohydrate, polyvinylpyrrolidone, and either lactose monohydrate or anhydrate when exposed to a temperature range of 23–120 °C. Near-infrared HSI and multivariate curve resolution – alternating least squares (MCR-ALS) successfully mapped the dehydration of piroxicam and lactose monohydrates separately in the samples, providing insights into surface heterogeneity during solid-state transformations. In [155], the authors used multi-series HSI in combination with Multivariate Curve Resolution – Alternating Least Squares (MCR-ALS) and Parallel Factor Analysis (PARAFAC and PARAFAC2) to monitor solid-state transitions on the surface of pharmaceutical solid dosage forms (SDFs). While challenges were encountered in resolving compounds, PARAFAC2 effectively extracted compound profiles in images during the dehydration of piroxicam and lactose monohydrates. For amorphous-to-crystalline transitions, MCR-ALS successfully resolved known drug forms, but PARAFAC and PARAFAC2 had limitations. This study explores the applicability and limitations of curve resolution methods in pharmaceutical solid-state transitions using multi-series HSI. In [156], the authors introduced a novel fiber-array-based Raman HSI technique for in-situ monitoring of active pharmaceutical ingredients (APIs) in analgesic tablets. This noninvasive method provides high spatial resolution down to 1 µm and revealed differences in API distribution between tablet types. It has potential for online quality control in pharmaceutical manufacturing, offering valuable insights into tablet production processes. In [157], the authors introduced HYPER-Tools, a user-friendly Matlab-based graphical interface for hyperspectral image analysis. It offers pre-processing methods, chemometric tools, and robust visualization, simplifying hyperspectral data exploration and making it more accessible for researchers and analysts.

In [158], the authors introduced a pixel-based identification (PBI) approach for efficiently identifying spectral signatures in Raman HSI data. This method effectively reduces the dataset while preserving pure spectral signatures and demonstrated remarkable efficiency in analyzing pharmaceutical formulations, including falsified tablets. It offers rapid and reliable spectral identification capabilities. In [159], the authors presented a HSI system using chip-scale semiconductor laser frequency combs operating in the terahertz spectral region. While it achieved high spectral resolution and compound identification, it has limitations in spectral coverage and frequency resolution. Future developments in terahertz quantum cascade lasers are expected to address these limitations, potentially enabling practical applications in bioimaging and pharmaceutical quality control. The use of pulsed mode operation and multiheterodyne downconversion is suggested as a viable path for such applications. In [160], the authors conducted a comparative study between PLS and MCR-ALS for analyzing Near-Infrared hyperspectral images of pharmaceutical tablets with Mebendazole polymorphs. PLS had lower prediction errors for average concentration but didn’t capture minor spectroscopic changes between polymorphs, resulting in less informative distribution maps. MCR-ALS provided more chemically meaningful distribution maps for all polymorphs. The choice between PLS and MCR-ALS depends on the analysis’s goal, whether global quantification or distribution analysis, highlighting the need to select the appropriate chemometric approach for HSI in pharmaceutical research and industry. In [161], the authors demonstrated the significance of reducing HSI data matrices by selecting essential spectra for analyzing complex pharmaceutical formulations using MCR-ALS. Experiments on both simulated and real datasets showed that MCR-ALS performed more accurately with reduced data matrices containing essential spectra. This approach has important implications for the analysis of complex pharmaceutical samples. In [162], the authors explored the use of computed microtomography for assessing the distribution of active pharmaceutical ingredients (API) in chocolate, specifically vitamins K and D and calcium.
They introduced image analysis algorithms to quantify API distribution without the need for 3D reconstruction. These methods enable a quantitative assessment of component homogeneity within the sample, proving valuable for evaluating API distribution in chocolate and other functional foods. In [163], the authors present the concept of autonomous adaptive data acquisition (AADA) for high-dimensional scanning HSI in biological systems. AADA is defined as a flexible building block for future biological imaging experiments, offering potential benefits in noninvasive imaging of living biological systems. In [174], the study tackles the challenge of distinguishing malignant melanoma from benign pigmented nevi in early stages. It utilizes HSI to capture tissue spectral features and employs deep convolutional networks with transfer learning for classification. The results indicate high accuracy, with potential for improving diagnostic precision and expediting the distinction between melanoma and nevus.

In [164], the authors discuss HSI as a promising “Next Generation Imaging” technique in clinical research, highlighting its advantages and applications in detecting carcinomas, classifying tissue structures, and assessing tissue blood flow. The conclusion emphasizes the need for optimizing algorithms, reducing redundancies, and expanding the HSI database for routine clinical use, particularly in intraoperative applications for tumor assessment. In [165], the authors discuss the growing significance of nanomaterials in cancer diagnosis and treatment, emphasizing the limitations of traditional techniques and introducing dark-field hyperspectral imaging (DF-HSI) as an affordable, label-free alternative. DF-HSI is capable of investigating cellular transport of nanoparticles (NPs) and monitoring microorganisms, single cells, and proteins. It also mentions integrating DF-HSI with other imaging modalities for chemical imaging and discusses potential applications in surgeries and future integrative approaches with other imaging techniques. In [166], the authors investigate the adsorption of various amides onto mesoporous silica (MS) through kinetic FTIR spectroscopic measurements. It identifies that N-methylpropionamide has the strongest affinity for MS, while tertiary amides show limited interaction. This behavior is related to the ability of amide N-H groups to form hydrogen bonds with the MS surface. The study suggests the potential for constructing effective qualitative hyperspectral sensors for amides using MS as a sensing substrate. In [167], the authors assess the use of the TIVITA® Tissue hyperspectral camera for diagnosing peripheral artery disease (PAD). It establishes correlations between TIVITA® Tissue’s oxygenation parameters and established PAD detection methods, showing that these parameters are indicative of PAD and can be used for screening and follow-up assessments. In [168], the authors offer an overview of hyperspectral fluorescence imaging (HFI) in medical research, highlighting its potential for non-invasive tissue diagnosis. It covers acquisition methods, preprocessing, feature selection, classification, and recent advances, including the fusion of unmixing techniques and applications in differentiating cancer cells.

In [169], the study aimed to create a non-invasive method for categorizing tooth abnormalities using HSI with a unique 395-nm laser diode source. It successfully differentiated between normal and abnormal dental conditions, identifying distinct wavelengths for various lesions. This approach offers a safe and effective way for dentists to diagnose and manage dental issues early. In [170], the study investigates the potential of using retinal HSI as a biomarker for brain amyloid beta (Aβ) levels in Alzheimer’s disease (AD). Significant differences in retinal reflectance spectra were found between individuals with high Aβ levels and those with mild cognitive impairment or controls. These findings were validated in an independent cohort and in transgenic mice, suggesting the potential of retinal HSI in AD research and diagnosis. In [171], the authors offer a comprehensive review of HSI applications in the medical field, focusing on disease diagnosis and surgical procedures. It explores the integration of HSI with machine learning, deep learning, genetic algorithms, and anomaly detection for medical applications. The survey highlights pre-processing methods, performance metrics, and the future potential of HSI in medicine, providing valuable insights for computer vision experts, machine learning researchers, medical professionals, and scientists aiming to improve medical treatments. In [172], the study presents a method for classifying different stages of periodontal disease using HSI. It involves simulating gingival image spectra and using a principal component score chart to categorize disease
stages. The results show accurate identification of normal gingiva, mild, moderate, and severe periodontitis, offering a precise means of disease staging with potential clinical applications. In [173], the study investigates the use of Raman hyperspectral imaging (HSI) as an alternative to compensated polarized light microscopy (CPLM) for identifying synovial crystals in rheumatic diseases. It detected various crystals, including classical and novel ones, offering advantages over CPLM and potential for discovering new crystal-based diseases, improving diagnostic accuracy, and monitoring. The study recommends further research and the creation of a Raman spectra database. In [175], the authors used HSI and optical coherence tomography to create a model for differentiating Alzheimer’s disease (AD) patients from controls via retinal imaging. The results demonstrated fair accuracy in distinguishing AD patients, and incorporating retinal nerve fiber layer thickness data improved the model. This study suggests the potential of HSI in AD diagnosis and highlights the benefit of combining retinal imaging modalities for improved diagnostics, though standardized data is needed for comprehensive understanding. In [176], the authors review the use of deep learning in medical hyperspectral imaging (MHSI) and highlights its growth, especially in cancer detection, using convolutional neural networks (CNNs). It mentions other deep learning approaches like fully convolutional networks (FCNs) and generative adversarial networks (GANs) for tasks such as tissue oxygenation assessment. The study suggests the potential of deep learning in MHSI but calls for more comprehensive reviews and further research to tackle challenges in this field. In [177], the authors discuss challenges related to high-dimensional medical imaging, particularly in multimodal HSI, super-resolution, and nanoimaging. It emphasizes the complexity of patient data and the improvements AI models bring to medical diagnostics and prognostics. However, it stresses the need to address real-world challenges in AI model performance due to high-dimensional data. The study suggests a holistic approach to AI in the medical field, including data management, automation, and the integration of hardware and software capabilities. In [178], authors proposed a new diagnostic approach using photonics and machine learning to detect early-stage skin complications in diabetes mellitus. This approach aims to non-invasively assess glycation and metabolic processes in biotissues, which can lead to complications like ulcers. The study’s results show the approach’s ability to differentiate between diabetic and control groups, offering potential advancements in age-related disease diagnosis and clinical assessments for diabetes patients. In [179], authors used HSI and convolutional neural networks (CNNs) to classify cancer margins in ex-vivo human surgical specimens. They introduced a novel method for generating HSI ground truth using histological cancer margins. The results suggest the effectiveness of HSI-based cancer margin detection with promising potential, particularly for thyroid carcinoma cancer-normal margins and squamous cell carcinoma.

In [180], the authors explore the use of HSI for early detection of oral cancer in a chemical-induced animal model. It introduces a novel classification algorithm to differentiate premalignant lesions from healthy tongue tissue, achieving an average area under the curve (AUC) of 0.89. This approach shows promise for noninvasive oral cancer detection, potentially enhancing early diagnosis and patient outcomes. In [181], the authors introduce a solution for enhancing the classification of medical hyperspectral images (MHSI) with limited samples. The approach involves a two-channel convolutional neural network (CNN) that combines global and local features to improve classification accuracy. In [182], the authors investigate the use of HSI to detect head and neck squamous cell carcinoma (SCC) in surgical specimens. Machine learning methods, including convolutional neural networks (CNNs) and support vector machines, are examined. Preprocessing and unsupervised segmentation enhance CNN performance, and even in regions with specular glare, a combination of CNN probability maps and segmentation yields a promising area under the curve value of 0.81. The study also explores margin variation with depth, suggesting HSI’s potential for intraoperative use in SCC detection. In [183], the authors present the application of HSI to differentiate normal and tumor breast cancer cells in histological samples. Their custom HSI system captured multiple images from human patient samples, and a deep learning neural network, trained with expert pathologist annotations, consistently achieved an impressive area under the curve (AUC) of over 0.89. In [184], the authors investigate the effectiveness of HSI in diagnosing and detecting solid tumors. HSI combines imaging and spectroscopy to acquire both spatial and spectral data from tissues, utilizing distinct spectral patterns to differentiate between cancerous and normal tissue. The review highlights the benefits of HSI in this context and its potential for various clinical applications, from label-free histopathological examinations to real-time intraoperative assistance. In [185], the authors explore the potential of HSI as a valuable tool for cancer analysis and detection. HSI’s ability to capture detailed spectral information beyond the visible spectrum allows for material differentiation based on spectral signatures. The review summarizes studies demonstrating HSI’s effectiveness in various cancer detection applications, both in-vivo and ex-vivo, while recognizing current technological limitations and dataset constraints. The paper concludes by stressing the importance of further research to establish HSI’s role in clinical and surgical contexts, ensuring its reliability and applicability in medical applications. In [186], the authors investigate the use of HSI coupled with advanced image processing and pattern recognition to detect breast cancer in ex-vivo tissues. It analyzes breast tissues’ optical properties based on spectral signatures and utilizes K-mean clustering for classification. In [187], the authors present a deep learning algorithm for automated oral cancer detection using hyperspectral images of patients. They utilized a partitioned deep Convolution Neural Network (CNN) with two partitioned layers to distinguish cancerous tumors from benign and normal tissue.

D. Safety and Security

Hyperspectral imaging (HSI) is instrumental in enhancing safety and security across various domains. In airport security, it helps identify concealed threats by analyzing the
spectral signatures of materials, improving passenger safety. In industrial settings, it detects gas leaks and chemical spills, preventing accidents and environmental hazards.

In [117], the authors emphasize the significance of utilizing advanced electrooptical tools, particularly HSI, for intelligence, surveillance, and reconnaissance (ISR) in modern defense scenarios. HSI provides high spectral resolution, enabling subpixel target detection, material analysis, camouflage detection, chemical agent identification, and improved image classification. The review delves into military and security applications, sensing capabilities, current technologies, and potential future advancements in HSI for defense purposes. In [118], the research centers on target detection in hyperspectral imagery, relevant to defense, search and rescue, and mineral exploration. It assesses eight signature-based hyperspectral target detection algorithms, including GLRT, ACE, SACE, CEM, MF, AMSD, OSP, and HUD, along with three anomaly detectors: RX, Maxmin, and Diffdet. Among these, three algorithms excelled and provided complementary insights. Through the fusion of these algorithms, the study successfully detected five out of nine targets with zero false alarms, underscoring the efficacy of fusion strategies in real-world hyperspectral target detection. In [119], the authors outline a method for military object detection using hyperspectral imagery (HSI). It underscores the importance of object detection in military applications and explores the potential of HSI in this context. The approach involves superpixel generation, spectral correlation calculations, and shape analysis to identify military targets. Results from HSI data confirm the method’s effectiveness in detecting specific military objects, offering a valuable strategy for HSI-based object detection. In [120], the authors present a rapid hyperspectral anomaly detection (HAD) technique that combines various features and isolation forest. This method is based on the assumption that anomalous pixels are more isolated compared to background pixels. It involves extracting spectral, Gabor, extended morphological profile (EMP), and extended multiattribute profile (EMAP) features from hyperspectral images and constructing isolation forests for each feature. By using a multi-feature approach that incorporates both spectral and spatial information, the method significantly improves anomaly detection performance. Comparative experiments with eight existing HAD methods on real hyperspectral datasets demonstrate the competitiveness of this approach in terms of accuracy and processing speed. In [121], the authors delve into the use of HSI in landmine detection, highlighting its safety and speed benefits. It presents various studies that concentrate on signal processing techniques applied to hyperspectral image data for detecting landmines. The aim is to underscore the progress in landmine detection achieved through HSI and to suggest future research directions for further improving real-time detection capabilities. In [122], the authors introduce an automated method for distinguishing targets from the background in hyperspectral images by utilizing prior target information. It treats hyperspectral images as a combination of low-rank background and sparse target components, obtained from a prelearned target dictionary. The study presents and evaluates two strategies for target detection, both in synthetic and real experiments, showing the efficiency of this approach. In [123], the authors concentrate on analyzing methods to convert raw hyperspectral data, particularly evaluating their quality and military suitability. It employs real experimental data to assess the quality of conversion by comparing it with laboratory measurements. The study offers insights into effective data conversion techniques for military applications. In [124], the authors explore the potential of ground-based HSI systems for detecting explosives and their traces from a distance, particularly in dynamic scenes with moving vehicles. It categorizes HSI systems as active and passive, and discusses methods for each category, including target detection algorithms and performance evaluation. Key challenges include experimental validation, spectral band registration, and addressing false positives, setting the stage for part II to address these issues with reflectance conversion solutions. In [125], authors address the challenges of using white references for reflectance conversion in ground-based hyperspectral image surveillance systems. It proposes three approaches to eliminate the need for frequent white reference measurements during surveillance: recording white reference radiance during system initialization, using affordable reference objects in the short-wave infrared spectrum, and utilizing the reflectance of static background materials in the scene. These approaches are compared and validated against baseline detection methods. In [126], the authors present a technical framework for ground-based hyperspectral image (HSI) surveillance systems designed for detecting explosive traces. This framework covers various stages, including data capture, preprocessing, reflectance conversion, target detection, and performance assessment. It leverages the short-wave infrared spectrum, which is sensitive to explosive characteristics. The study evaluates three classes of detection methods, with a hybrid structure detector offering the best precision and recall performance. Deep-learning-based methods show promise but require improvements in recall rates, possibly with more data in the future.

In [127], the authors emphasize the importance of efficient reconnaissance technology for identifying camouflaged targets in modern warfare. It highlights the value of hyperspectral images with their wide spectral range and high resolution for distinguishing these targets from their backgrounds. The authors introduce a two-step approach, utilizing constrained energy minimization (CEM) for single-class camouflage target detection and support vector machine (SVM) for multi-class camouflage target classification. Experimental results demonstrate the effectiveness of this method in camouflaged target reconnaissance.

In [128], the authors introduce an innovative strategy for efficiently reconstructing hyperspectral images with fewer measurements, focusing on reliability-weighted sampling. This method is applied to detect hidden hardware Trojans in integrated circuits, achieving superior performance with significantly fewer measurements than previous methods. The study evaluates different sampling rates and sparsity levels, highlighting the potential for high-throughput IC validation, although further research is required for various circuit types and real-time applications. In [129], the authors delve into camouflage target recognition using short-wave infrared HSI.
results show that this detection method is robust against smoke focusing on the 2015 Esperance wildfire as a case study. The satellite’s high-temporal-resolution multispectral imagery, wildfire extent monitoring in Australia. The study assesses investigate the use of the Himawari-8 satellite for real-time est health assessment and management. In [132], the authors scale disease trends. This multi-sensor approach improves for- a comprehensive platform for precision forest management, suggests that combining these sensor technologies can provide data for broader-scale stress trends over larger areas. The study evaluates for fine-grained, individual tree-level monitoring, and satellite both data sources are effective, with UA V data being better and moderate cloud cover, enabling early wildfire detection. It also allows real-time tracking of detailed wildﬁre detection in fire spread rates and directions, potentially enabling automated detection of abnormal fire behavior. This research underscores the satellite’s value in improving wildﬁre monitoring and response capabilities. In [133], the authors discuss the need for continuous forest fire monitoring and early detection using Unmanned Aerial Vehicles (UAVs). It introduces a UAV-based system for real-time wildﬁre surveillance, which includes features like fire source identiﬁcation, location, size estimation, and an LCD module. The paper also presents algorithms for color code identiﬁcation, smoke motion recognition, and fire classiﬁcation. It highlights the challenges posed by com- plex forest conditions, smoke interference, and UAV camera movement in achieving accurate forest fire detection. The study underscores the importance of developing reliable and precise forest fire detection algorithms for UAVs to reduce false alarms and improve detection in various conditions. In [134], the authors discuss the evolution of wildﬁre detection and monitoring techniques, focusing on the potential of new sensor technologies and affordable sensor platforms, including unmanned aircraft (drones). It explores the current state of fire detection from both manned and unmanned aerial platforms, highlighting their operational constraints and opportunities. The conclusion emphasizes the ongoing importance of airborne detection in forest management and the potential for hierarchical sensor systems, continuous monitoring, and small sensing platforms to enhance wildﬁre suppression efforts. In [135], the authors discuss the challenges of nighttime fire detection on roads using standard RGB cameras and introduces a solution using hyperspectral cameras with multiple bands to differentiate between ﬂames, vehicle lights, and roadside lighting based on spectral information. The proposed method employs NKNBD (Normalized K and NIR Band Difference) in hyperspectral cameras for accurate ﬁre detection, improving reliability in distinguishing ﬂames from other sources of light in road environments at night. In [136], the authors discuss the critical issue of wildﬁre detection and its implications for climate change, emphasizing the application of space-borne tech- nology and artiﬁcial intelligence for accurate and rapid wildﬁre detection. It presents the development and testing of convolu- tional neural networks adapted for trusted autonomous satellite operations (TASO) to detect wildﬁres. The study evaluates the performance of hardware accelerators for edge computing in analyzing hyperspectral data for wildﬁre detection. The results highlight the potential of onboard data processing for disaster management and climate change mitigation, suggesting the use of hardware accelerators in future space missions to enhance services and improve disaster management. In [137], the authors introduce a wildﬁre segmentation study using PRISMA hyperspectral data and a methodology that incor- porates convolutional neural networks (CNNs) and transfer learning. PRISMA, a satellite launched by the Italian Space Agency, provides high-resolution spectral data. The authors utilized PRISMA data from the 2019 Australian bushﬁres to train a one-dimensional CNN and applied transfer learning to detect wildﬁres in the 2021 Bootleg Fire in Oregon. The study evaluates the network’s ability to generalize and suggests
potential future applications. It underscores the effectiveness of hyperspectral data and CNNs for wildfire detection. In [138], the authors examine the application of artificial intelligence and edge computing for wildfire detection using satellite platforms, with a focus on the Italian hyperspectral satellite PRISMA. It presents findings from the analysis of data related to the December 2019 Australian bushfires as observed by PRISMA. The study delves into the implementation of a one-dimensional convolutional neural network (CNN) and explores the utilization of hardware accelerators such as Intel Movidius Myriad 2, Nvidia Jetson TX2, and Nvidia Jetson Nano for executing CNN computations at the edge. This research contributes to improving onboard computing capabilities and platform autonomy, potentially enabling future satellites to provide real-time, dependable early wildfire warnings.

In [139], the authors tackle the growing threat of wildfires and the crucial need for early detection to mitigate their impact. It introduces an autonomous system that leverages satellite imagery for wildfire monitoring. The proposed method utilizes advanced deep learning for pixel-level wildfire detection and includes an interactive dashboard for analysis. Tested on GOES-16 data, the system achieves an impressive performs 1.5 times faster detections, demonstrating its resilience in the face of different wildfire types and adverse conditions. This approach presents a promising solution for early wildfire detection and mitigation. In [140], the authors explore the accomplishment of swift broadband spectral tuning in External-cavity quantum cascade lasers (EC-QCLs) by integrating a MOEMS scanner with a diffraction grating. It showcases real-time spectroscopic sensing with applications in hazardous substance detection and food quality monitoring. The MOEMS EC-QCL, featuring a high-speed scanning grating at 1 kHz, enables rapid data collection, substantially cutting down acquisition times. The outcomes affirm the viability of this technology for dynamic chemical reaction tracking and the identification of hazardous materials across different distances, underscoring its potential utility in diverse spectroscopic applications. In [141], the authors introduce a technique to establish a standardized spectral library for the identification of hazardous chemical solvents in riverine settings through the use of UAV-based hyperspectral imagery. The process entails defining hazardous substances using hyperspectral sensors, extracting their spectral signatures, and constructing a dedicated library. This method provides a non-contact and effective means to monitor hazardous chemical spills in rivers, mitigating the constraints associated with traditional contact-based measurement approaches. In [142], the study explores the application of HSI for the detection and recognition of hazardous chemicals. They employ a combination of spectral curve matching based on full-waveform characteristics and spectral matching based on spectral properties. Results indicate that certain chemicals with distinct spectral curve characteristics and color can be easily identified. However, chemicals lacking obvious spectral characteristics require consideration of color information for identification. The research also introduces a quantitative method to assess the matching degree of spectral curves, which correlates with reflectivity for specific chemicals. This has implications for the early detection and warning of hazardous chemicals using HSI.

In [143], the authors discuss the problem of water pollution from chemical leaks and spills, particularly the challenges of detecting colorless and water-soluble chemicals in water bodies. It points out the limitations of traditional contact-based detection methods and proposes the use of HSI for remote chemical detection in aquatic environments. The study focuses on creating a spectral library for 18 hazardous chemicals and examines the potential to classify these chemicals individually using hyperspectral imagery. The paper emphasizes the need to expand the spectral library database and apply this technology in real-world scenarios to enhance the rapid detection and response to chemical spills. In [144], the authors present an innovative method for nondestructive detection of natural gas microleakage using UAV hyperspectral imagery. It combines a crop growth model (SAFY) with a convolutional neural network (CNN) approach to evaluate environmental stress on wheat as an indicator of natural gas leakage intensity. The SAFY model’s natural gas stress index (Kgs) effectively identified leakage levels, demonstrating statistical significance. The CNN-1D model with InceptionV2 architecture exhibited high accuracy in estimating Kgs, with robustness throughout the wheat growth period. This approach proves more robust than traditional spectral index-based methods, offering a promising solution for nondestructive natural gas leakage detection. In [145], the authors address the challenge of detecting underground natural gas storage leaks by analyzing spectral changes in surface vegetation. To improve accuracy, a novel spectral-spatial methodology was proposed, which involved creating a circular detection model by extracting and segmenting vegetation and color indices and using shape parameters. While individual detection accuracies were relatively low, accurate detection and localization of all leakage points were achieved without false alarms by fusing the results based on the spatial distribution pattern of stress zones. In [146], the study aims to detect natural gas leakage in vegetated areas using high spatial resolution hyperspectral imagery. It introduced a new vegetation pixel extraction method to address shadow issues in high-resolution images. By applying spectral analysis techniques, including continuum removal (CR) and variational mode decomposition (VMD), a spectral index called CVI (Continuum removal - Variational mode decomposition Index) was created to assess vegetation stress. Threshold segmentation methods were then utilized to precisely identify the extent and location of gas leakage. This research underscores the potential of high-resolution hyperspectral imagery for monitoring the impact of natural gas leakage on vegetation, providing valuable insights for relevant authorities and stakeholders.

E. Industrial, Manufacturing, Management, and Conservation

Hyperspectral imaging (HSI) plays a pivotal role in industrial and manufacturing processes by inspecting product quality, identifying defects, and ensuring consistency in production lines, thereby enhancing efficiency and reducing waste. In resource management, it aids in monitoring and conserving precious natural resources, such as forests and water bodies, by assessing environmental changes and detecting anomalies.
Additionally, HSI contributes to heritage conservation efforts by analyzing and preserving historical artifacts and artworks through non-invasive spectral analysis.

In [62], the authors introduced an innovative method utilizing HSI for the efficient analysis of marine microplastic litter. HSI was applied to samples collected from various global regions, providing valuable data on abundance, size, shape, and polymer composition of plastic particles in each sample. This simultaneous characterization of plastic debris, particularly the polymer type, addresses a common challenge in microplastic pollution analysis. HSI emerged as a rapid, non-invasive, and reliable technology for microplastic waste characterization, offering great potential to enhance plastic pollution monitoring efforts. In [63], the authors propose a plastic classification model using near-infrared spectroscopy (NIR) in the wavelength range of 1000–2500nm. This model is designed to characterize and sort various types of plastics, including ABS, PS, PP, PE, PET, and PVC. It relies on principle component analysis (PCA) to identify feature wavelengths from standard samples. The model’s simplicity, consisting of a basic equation, center of mass coordinates, and radial distance, makes it suitable for developing classification and sorting software. This model holds potential for online plastic characterization and sorting in waste recycling. In [64], the authors proposed an innovative approach to extract PVC from window frame waste, using a combination of magnetic density separation (MDS) and HSI. MDS, known for its precision in density separation, was employed to obtain high-grade PVC pre-concentrates due to PVC’s distinctive high density. HSI was then utilized to ensure the quality of the separated products, effectively discriminating PVC from unwanted rubber particles with different colors. In [65], the authors highlight the potential of HSI in waste recycling, both in laboratory development and industrial sorting, to address challenges in material classification and identification, particularly for difficult-to-handle contaminants. HSI, along with chemometric approaches, was successfully applied in analyzing concrete and mixed plastic waste, offering flexible, cost-effective, and reliable solutions for detection and control.

In [66], the authors explore novel applications of HSI for plastic waste management and recycling, including addressing environmental issues like marine microplastics and improving plastic recycling processes by identifying and separating different types of plastics. HSI, combined with chemometric methods, offers valuable insights into sustainable plastic waste management practices. In [67], the author’s research focuses on estimating the concentration of pigment blue 15:3 in LDPE plastic using HSI systems. They developed two models, with the principal component-based model performing better, and this approach has potential applications beyond pigment estimation in plastics, contributing to addressing plastic waste challenges. In [68], the authors explored the use of HSI to monitor the production of a biowaste-derived fertilizer, achieving strong correlations between spectral features and physical-chemical parameters. This approach offers a rapid and non-destructive method for monitoring fertilizer production, especially when compared to traditional laborious and time-consuming analyses. In [69], the authors discuss recent advancements in HSI and its integration with Machine Learning and Deep Learning algorithms for accurate material classification in waste recycling. This combination of HSI and AI techniques improves efficiency in waste sorting and contributes to sustainable recycling practices, reducing risks associated with handling hazardous waste. In [70], the authors propose an in-line method using HSI and principal component analysis (PCA) to accurately estimate the flame retardant ammonium polyphosphate (APP) in plastic waste, particularly in low-density polyethylene (LDPE) and polypropylene (PP). This method provides a fast, non-destructive, and cost-effective solution for plastic recyclers and waste management industries to quantify flame retardant content during recycling, thereby improving the safety and sustainability of plastic recycling processes. In [71], the authors present an innovative method that integrates HSI technology with a specialized Artificial Neural Networks (ANN) algorithm to accurately identify and separate different types of e-waste plastics (e-plastics). Through the optimization of the ANN algorithm and the utilization of hyperspectral signatures, the study demonstrates a high level of accuracy in distinguishing three common e-plastic types, offering a promising solution to improve the efficiency and reliability of e-plastic sorting processes and address current limitations in the recycling industry. In [72], the authors present an innovative method for accurately categorizing different polymers within complex plastic waste streams, which is a critical requirement in plastic recycling. This method combines HSI in the near-infrared (NIR) range with image segmentation techniques, including entropy and contrast stretching, to identify distinct objects in hyperspectral images. This approach has the potential to be a cost-effective and precise solution for polymer classification in
In [74], the study investigates the use of HSI to predict microbial contamination in stored bovine hide samples by predicting aerobic plate counts (APC). HSI, combined with partial least squares regression, showed good accuracy in predicting APC levels, indicating its potential as a non-invasive tool for real-time grading of hides and improving efficiency in leather processing. In [75], the authors explore the use of HSI in combination with the XGBoost algorithm to classify various industrial organic waste materials. XGBoost outperforms traditional methods in terms of accuracy and prediction time, suggesting that this approach could be valuable for developing an online waste sorting platform, providing cost savings and accurate waste identification. In [76], the authors explore the use of HSI for non-destructive testing of carbon fiber reinforced polymer (CFRP) materials. It includes three case studies showcasing the effectiveness of HSI in detecting damage and material composition differences in CFRP, making it a valuable tool for industrial manufacturing applications. In [77], the authors discuss the issue of electronic waste from flat panel screens and investigates the use of HSI to identify valuable thermoplastic polymers such as polycarbonate (PC) and polymethyl methacrylate (PMMA) in these screens. The study demonstrates the potential of HSI combined with chemometric methods for non-invasively recognizing and separating plastic fragments in electronic waste, which can aid in recycling and quality control efforts. In [78], the authors explore the use of HSI and chemometric methods to identify and separate Asbestos-Containing Materials (ACMs) in Construction and Demolition waste (C&DW). ACMs present health hazards and need to be isolated during recycling, and HSI operating in the short-wave infrared range proved effective in automatically and non-destructively detecting ACMs within C&DW, although there is a pixel resolution limit for fiber detection. Further data collection and analysis could improve ACM identification in C&DW, enhancing safety and reducing errors in recycling processes. In [79], the authors demonstrate the application of Hyperspectral Cameras (HSC) for the identification of road defects such as cracks and potholes. By analyzing the spectral differences between road pavement and surface materials, particularly in the spectral range of 450nm-550nm, the study introduces a new metric to measure metal oxide changes, offering an effective method for rapidly detecting areas in need of road maintenance or repair. In [80], the authors present a novel approach for the early detection of road pavement cracks using HSI. By introducing the Asphalt Crack Index (ACI), which measures material changes in the spectral range of 450–550 nm, this method outperforms traditional metrics, offering a more effective way to identify road cracks and facilitate timely repairs and maintenance. In [81], the authors introduce a mobile HSI system for automated damage inspection of structural materials. By employing machine learning and feature extraction techniques, it achieves high accuracy in detecting cracks and complex objects on material surfaces, showcasing the potential of HSI for more effective and precise damage detection in built structures, surpassing traditional gray-valued images in performance. In [82], the authors propose the use of remotely operated vehicles equipped with HSI systems and machine learning algorithms to detect corrosion in steel infrastructure. HSI, offering both spatial and spectral information, proves valuable for material characterization and classification based on chemical properties in reflection spectra, offering a potential solution for efficient corrosion inspections in complex environments. In [83], the authors discuss the use of UAVs for monitoring and inspecting critical infrastructure, focusing on detecting corrosion. It highlights the integration of hyperspectral sensing on drones and an improved software workflow for handling hyperspectral imagery to detect material degradation. The paper also presents a processing pipeline that includes preprocessing, on-board analysis using neural networks, and post-processing to overlay detected corrosion defects on 3D infrastructure models, showing promising results with high accuracy in corrosion detection. In [84], the authors propose using a swarm of unmanned aircraft systems equipped with HSI to efficiently inspect transportation infrastructure like roadways, railways, and pipelines. This approach aims to overcome the limitations of current inspection methods by capturing high-resolution images with polarization diversity to isolate infrastructure targets, using structure-from-motion techniques for 3D reconstruction, and selecting wireless communication standards for coordination. The paper also presents a taxonomy of defects and anomalies that the proposed system can identify and assess for risk estimation. In [85], the authors discuss the significance of maintaining civil infrastructure in Malaysia, driven by economic growth. It explores the use of hyperspectral and infrared thermal sensors for non-destructive monitoring of civil structures, detecting road distress, and analyzing vegetation. The paper also introduces a Pavement Condition Index (PCI) table to assess road distress and discusses the feasibility of using hyperspectral sensors and imagery for civil structure maintenance and monitoring. In [86], the authors highlight the growing significance of HSI, which was once limited to specialized research teams, but is now gaining commercial traction. It discusses the potential application of HSI systems in conducting aerial surveys of outdoor power lines, leveraging current technological advancements. In [87], the authors investigate the use of hyperspectral images for detecting and classifying cracks on concrete structures as part of infrastructure monitoring and maintenance. Unlike traditional binary image processing, this study explores the potential of hyperspectral data, spanning various wavelengths, to identify cracks, even in challenging conditions such as biological colonization. The research involves concrete specimens with intentionally induced crack patterns and applies the k-means algorithm to cluster hyperspectral data. This approach shows promise for on-site crack detection, offering potential advantages for maintenance planning and strategies. In [88], the authors discuss the increasing significance of color accuracy in the automotive industry and how it impacts manufacturers and suppliers. It explores the application of HSI alongside traditional color science techniques to assess color differences in automotive parts. Using the Specim FX10 hyperspectral camera, the research showcases the potential of HSI for real-
pigments in paintings. By combining processing steps and a
reference pigment database, the study confirms the feasibility
of this approach, demonstrating its potential in art conserva-
tion. The results showcase the capabilities of HSI and set
the stage for further advancements in pigment recognition
algorithms.

In [95], the authors introduce a novel method and tech-
nology for identifying painting materials using HSI, spec-
tral libraries, and classification strategies, enhancing the di-
agnostic capabilities of visible-near-infrared imaging spec-
troscopy. They combined a hyperspectral camera with in-
novative electro-optic tunable filters and employed various
spectral analysis and classification algorithms. Through the
creation of pigment replicas and extensive spectral data, the
Maximum Likelihood algorithm demonstrated superior per-
formance in identifying pigments used by El Greco and his
workshop. This approach holds significant potential for sci-
entific analysis, conservation, and authentication of artworks.

In [96], the authors trace the evolution of HSI in cultural
heritage, highlighting its transformation from its introduction
in the 1990s to its current versatile applications. HSI has
become a valuable tool for non-invasive monitoring, high-
quality documentation, and various other cultural property-
related tasks. Recent advancements, including applications
in photographic materials and color analysis for restoration
support, along with user-friendly, portable HSI devices, are
expanding its use in different contexts. In [97], the authors
evaluated the capabilities of two HSI systems in analyzing
Goya’s paintings at the Museum of Zaragoza. These systems
generated reflectance spectra, which were compared to a
reference database, revealing restored areas through false-color
infrared images. While HSI facilitated the identification of
main pigments, confirmation via portable Raman Spectroscopy
and hand-held X-ray fluorescence was required due to pigment
complexity and the presence of varnishes and binders. This
method offers a potentially faster way to survey paintings
and aids in extensive comparisons for art history research.

In [98], the authors recommended the adoption of HSI, in
conjunction with signal processing and classification methods,
as a valuable asset in improving art authentication by detect-
ing forgeries. They developed a spectral library of specific
pigments and showcased the ability to train and employ classi-
fication techniques using this dataset. Their method effectively
detected anachronistic paint in real forged artworks, providing
confirmation of their fraudulent nature. The paper emphasizes
the potential of infrared HSI in the domain of art authentica-
tion and highlights the benefits of collaboration between art
historians and signal processing experts for successful results
in this area. In [99], the authors suggest an alternative method
to generate high-contrast FT-IR images from hyperspectral
data obtained through reflection µ-FTIR analysis of historical
artifacts. Conventional techniques often encounter challenges
related to surface quality and spectral artifacts, leading to un-
certain outcomes. The authors propose the use of multivariate
statistical analysis, particularly Hierarchical Cluster Analysis
(HCA) validated with a supervised Principal Component-
based k-Nearest Neighbor (PCA-kNN) Analysis, to reconstruct
µ-FTIR images with precise chemical distribution details.

In [100], the authors present a novel technique, HSI, as
a precise method for measuring colors in art conservation, especially in document analysis. The study investigates the repeatability and reproducibility of color parameters obtained from hyperspectral data. Test samples included commercial color standards and pen ink lines, revealing variations in parameter determination, likely due to limited pixel data. The research establishes an optimal HSI acquisition method to accurately determine spectral characteristics. Furthermore, the study demonstrates HSI’s effectiveness in monitoring color changes in real-life examples, such as documents treated with low-temperature plasma, offering a valuable alternative to traditional colorimetry. In [101], the authors introduce an innovative Fourier transform hyperspectral camera for cultural heritage analysis. It discusses its advantages and limitations compared to traditional methods and proposes strategies to overcome limitations, such as balanced illumination and high dynamic range data acquisition. The camera is deemed suitable for in-situ investigations in museums and archaeological sites, offering robust performance even in challenging lighting conditions. The hyperspectral data allows for pigment mapping and material identification. In [102], the authors present a study of The Pentecost, a Mexican Colonial painting attributed to Baltasar de Echave Orio. It uses noninvasive techniques, including reflected HSI, UV fluorescence photography, and X-ray radiography, to analyze the painting’s pigment distribution and conservation status. The study also involves analyzing paint mock-up samples and uses spot analytical methods like fiber optic reflectance spectroscopy (FORS) and X-ray fluorescence spectroscopy (XRF) to identify the artist’s materials. In [103], the authors introduce a chemometric approach for analyzing colorants on ancient illuminated manuscripts using hyperspectral images. It employs techniques like spectral de-noising and image analysis to separate and map colorants efficiently. The identification of colorants is supported by extracting and interpreting VNIR spectra and using a portable X-ray fluorescence (XRF) spectrometer. This approach has potential for broader applications in historical document analysis. In [104], the authors explore the use of HSI to noninvasively evaluate heritage objects, focusing on a beehive panel painting. HSI, utilizing four cameras with different spectral ranges, aims to identify pigments, binders, and their distribution on the artwork’s surface. This approach, combined with reference databases, aids in identifying original materials and detecting conservation interventions. HSI is shown to be a valuable tool for detailed examination of artworks, offering insights into pigment composition and distribution alongside traditional techniques like X-rays. In [105], the study explores the preservation of a century-old traditional blouse from Romania using a combination of traditional and innovative methods. It involves the application of silver nanoparticles and lye washing to assess their antimicrobial properties. HSI confirmed the penetration of silver nanoparticles into the fabric, and microbiological analysis showed a significant reduction in bacterial colonies. The antibacterial effect was long-lasting, making silver nanoparticles a promising option for textile preservation without causing fabric damage, aligning with non-invasive conservation approaches for heritage objects.

In [106], the authors introduce a specialized transmittance HSI scanner designed for non-invasive analysis of photographic materials, such as negatives, films, and slides. Testing in the lab and on damaged specimens shows its potential for large-scale spectroscopic characterization of photographic archival materials. While direct material identification is challenging due to complex layering, the spectral data can create accurate digital copies and be processed for damage detection and detail recovery. This approach offers promise for conserving and restoring photographic heritage, potentially reconstructing images from damaged originals. In [107], the authors explore the application of infrared thermography and HSI to detect defects and anomalies in a canvas painting resembling Botticelli’s “Venus.” Statistical algorithms like principal component and independent component analyses improve defect detection in both methods. The study shows that pulse-compression thermography with low-power LED sources effectively detects inner layer defects. Combining thermography and HSI through image fusion provides a comprehensive map of pentimenti and defects, offering potential benefits for restoration decisions. In [108], the authors report on a Round Robin Test conducted by ten European institutions to evaluate multispectral and hyperspectral reflectance imaging systems for digitizing a Russian icon from 1899. Results showed variations in image quality due to differences in spatial resolution and issues like unwanted reflections from glossy and metallic areas. Specular reflection impacted reflectance spectra accuracy, emphasizing the importance of illumination control. The paper highlights the necessity for standards in digitizing cultural heritage objects to ensure consistent system performance. It also underscores the significance of metadata recording, calibration, and regular system testing for accurate digitization and color reproduction. In [109], the authors discuss the HSI of the Gough Map, an early 15th-century British map. HSI was used to enhance faded text and analyze the pigments used in the map. Different analytical methods, including the Gram matrix approach, were applied to study the diversity of red pigments on the map. The results identified at least five distinct red pigments with a specific spatial pattern. This research provides historical geographers and cartographic historians with a valuable tool to assess the material diversity of cultural heritage artifacts using HSI. In [110], the authors present an innovative virtual restoration technique for eliminating stains from ancient Chinese paintings, preserving their authenticity and worth. This method utilizes HSI and the maximum noise fraction (MNF) transformation in a two-step process. Initially, it condenses the essential aspects of the artwork into top principal components. Subsequently, it identifies the principal component containing stain information and employs the inverse MNF transformation to minimize the stain’s effect, restoring the original spectral data and colors. Experimental outcomes on a Qing Dynasty paper painting showcase the approach’s efficacy in reducing or eliminating image stains while maintaining the painting’s style and data integrity. In [111], the authors present a workflow that utilizes visible and near-infrared hyperspectral technology for the management, monitoring, and conservation of rock art, an important but delicate cultural heritage. This methodology improves the documentation of rock art by uncovering pre-
orious unseen details and enabling non-invasive recording to protect the artworks from harm. Through the integration of geomatics techniques and hyperspectral data, it provides a comprehensive and wide-ranging perspective of rock art, even in non-visible parts of the electromagnetic spectrum. In [112], the authors explore the use of Hyper-Spectral Imaging technology in Cultural Heritage (CH), specifically for large outdoor murals and archaeological sites. In an archaeological site in Pompeii, avionic HSI with the SIMGA sensor was tested. The findings demonstrated that HSI is effective in identifying pictorial materials, mapping their distribution, and detecting degradation markers such as gypsum on wall paintings. Moreover, it showed potential for enhancing faded parts of partially lost mural inscriptions in archaeological settings. In [113], the research aimed to use HSI to identify the origin of obsidian rocks used by ancient civilizations. They employed hyperspectral cameras and supervised algorithms but found that solely relying on spectral signatures couldn’t effectively distinguish between Gran Canaria and Tenerife obsidian rocks at various classification levels. Success was observed at the island level but became less effective at lower levels, possibly due to differences in obsidian types. In [114], the authors introduce a multi-analytical approach for studying the Corale 43 illuminated manuscript, dating back to the 15th century. Using non-invasive techniques and portable devices like Vis-NIR FORS, XRF, and HSI, the authors identified pigments and mapped pictorial materials on the manuscript’s surface. This analysis provided insights into the pigment palette and contributes to research on Fra Angelico’s artistic production. Comparisons with other manuscripts offer additional insights into materials and techniques from the same period and region. In [115], the authors explore the potential of Unmanned Aerial Systems (UASs) in conservation management, highlighting their ability to provide high-quality data using advanced sensors. However, it notes limitations such as flight range, animal detection challenges, and data handling complexity. The use of SWIR cameras and polarization filters is suggested to improve animal detection, but further testing is needed. Legal constraints and costs are also mentioned. The paper concludes that UASs are valuable for data collection but should be used alongside other methods in conservation management. In [116], the authors discuss the utilization of high-resolution hyperspectral data from NEON to map and study vegetation changes in rangelands over 5 years. The data’s detail enabled differentiation between plant community types, and weather had a greater influence on composition than management. The study underscores the importance of advanced data handling skills and interdisciplinary collaborations for ecological research and offers practical applications for rangeland management and conservation.

IV. FUTURE CONSIDERATION

In the realm of future research, there are numerous exciting possibilities in the field of hyperspectral imaging. Future exploration can delve into the synergies between hyperspectral and LiDAR (Light Detection and Ranging) data, amplifying their potential for environmental monitoring, forestry practices, and land management. This fusion of technologies offers the promise of richer 3D insights into objects and landscapes. Pioneering real-time hyperspectral imaging systems could usher in a revolution, particularly in fields like medical diagnostics and precision agriculture. Researchers may embark on studies to assess the feasibility of compact, high-speed hyperspectral sensors for instant data acquisition and swift decision-making. The integration of deep learning techniques, such as convolutional neural networks (CNNs) and recurrent neural networks (RNNs), into hyperspectral data analysis, holds the potential for more precise and efficient classification and object detection. The horizon of research may focus on refining deep learning architectures tailored specifically to hyperspectral data. Efforts should be channeled into miniaturizing hyperspectral sensors and reducing their cost, thereby broadening their accessibility across a spectrum of applications and users. This democratization of hyperspectral imaging technology could usher in novel areas of research. Collaborative efforts between hyperspectral imaging experts and domain-specific professionals, such as medical practitioners, ecologists, and geologists, can birth innovative applications. Interdisciplinary research holds the promise of uncovering novel insights and problem-solving approaches. The establishment of standardized protocols for hyperspectral data collection, storage, and sharing stands as a crucial objective. A unified approach would facilitate collaboration, result comparison, and the creation of comprehensive hyperspectral databases for research and practical applications. The utilization of hyperspectral sensors on drones and unmanned aerial vehicles (UAVs) is on the ascent. Future endeavors may concentrate on optimizing these platforms for a range of applications, encompassing disaster response, precision agriculture, and environmental monitoring. Hyperspectral imaging can wield significant influence in the realm of environmental impact assessment for large-scale projects. Research in this sphere can contribute substantially to fostering sustainable development and informed land use planning. In the medical domain, the fusion of hyperspectral imaging with bioinformatics can birth advanced diagnostic tools. Prospective research can explore the promise of hyperspectral data in early disease detection and personalized medicine. Initiatives directed toward crafting user-friendly software tools for hyperspectral data analysis can facilitate the broader adoption of this technology across diverse domains. These tools should feature intuitive user interfaces and data processing pipelines designed with non-experts in mind. As hyperspectral imaging technology advances, ethical considerations concerning privacy, data security, and potential misuse warrant careful deliberation. Future studies can delve into the ethical dimensions of hyperspectral data collection and utilization.

In summation, these future considerations underscore the vast potential for continued growth and innovation within the realm of hyperspectral imaging applications and algorithms. They underscore the importance of interdisciplinary collaboration, technological progress, and ethical consciousness to guide the responsible utilization of this dynamic field.


[118] Mustafa Kütük, İzlen Geneci, Okan Bilge Özdemir, Alper Koz, Okan Esendürek, Yasemin Yardımcı Çetin, A. Aydın Alatan, Ground-Based


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