Chapter 3.9

Growing applications of hyperspectral and multispectral imaging

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1. Forensics

Forensic science deals with the physical and chemical analyses of physical evidence collected in crime scenes, with the aim of supporting investigators in solving crimes. The analysis of forensic traces includes a wide range of applications, like the visualization of latent bloodstains, the identification of fingerprints, or the characterization of gunshot residue, each one with a specific target and a specific analytical protocol [1]. Since standard analytical techniques commonly adopted by forensic scientists are often destructive and time consuming, there is an increasing demand for fast, noncontact, and nondestructive analytical methods to be employed in forensic determinations.

In this context, forensic applications using hyperspectral imaging (HSI) are constantly growing thanks to the possibility of performing real-time analysis in a nondestructive and noncontact manner. Benchtop hyperspectral systems could be easily incorporated into the analysis workflow to provide valuable information in forensic casework, while future perspectives may include the possibility of bringing dedicated hyperspectral systems directly to the crime scene.

1.1 Identification of gunshot residue

In the reconstruction of firearm-related offenses, e.g., murders, suicides, or accidents, the study of gunshot residue (GSR) is of fundamental importance

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for forensic investigators. GSR is a complex mixture of particles produced during the shooting, including gunpowder, primer residue, and metal particles derived from the bullet and the cartridge case [2].

The pattern formed from GSR on the target depends on the firing distance and other conditions, like the type of ammunition. In particular, it has been demonstrated that the amount, density, and distribution of GSR particles are strictly related to the shooting distance. In particular, there is an exponential decrease of GSR particles with increased shooting distance [3].

Traditionally, forensic analysts estimate the shooting distance based on visual evaluation of GSR patterns and by comparing them with reference standards produced under controlled conditions. In addition, color tests based on chemical reactions can also be performed to enhance the visualization of GSR [4]. However, visual assessment can be strongly limited by the substrate of the target, for example, different fabric colors. For these reasons, some applications of spectroscopic and imaging techniques have been evaluated for their ability to reveal GSR patterns [5–7]. As an example, Zapata el al. [8]. used a multispectral imaging (MSI) system working in the visible (Vis) and near-infrared (NIR) ranges to visualize GSR patterns on clothing targets placed at different distances. The number of pixels of GSR particles was correlated with the shooting distance through an exponential mathematical equation, and this equation was applied to validate samples with successful results.

An advance in GSR analysis consists in the addition of markers with metal–organic frameworks (MOFs) to ammunitions to improve the analysis routine. Furthermore, the use of various markers could allow one to link an ammunition type to specific markers [9]. The conjunction of NIR HSI and multivariate analysis has been successfully tested as an effective analytical tool for the distinction of GSR particles containing different MOF-based markers [10].

1.2 Nondestructive detection of forensic traces

A crucial aspect in crime scene investigations is the identification and detection of forensic traces, including explosives and body fluids [11].

1.2.1 Explosives

Due to recent terrorist attacks, explosive detection has become a topic of utmost importance in forensic sciences. Furthermore, the identification of explosives is an important task to establish connections between suspects and crime scenes. In particular, there is a specific need for noncontact and nondestructive analytical procedures, which can also be employed in situ in public places like airports, hospitals, and general public events to prevent potential dangers to public security. In this context, HSI represents a possible solution, and several research studies have been conducted to evaluate the ability of this technique to detect explosive residues of a wide range of substrates [12].

For example, HSI has been successfully applied to image latent fingerprints to detect trace information about explosives residues [11,13,14]. In Bhargava et al. [15] infrared HSI coupled with proper image analysis techniques allowed the identification of the spectral features of the explosives under investigation and the use of this information to identify and locate target substances on the fingerprints. Similarly, de la Ossa et al. [16] evaluated the possibility of using NIR HSI to identify residues derived from the manipulation of explosives in the whole handprint. Classical explosives, including ammonium nitrate, nitrocellulose, black powder, and dynamite, were manipulated by volunteers and, after manipulation, their handprints were collected on polyvinyl film sheets. Hyperspectral images of the plastic sheets containing the handprints were used to create a library of spectral profiles of the target substances and to obtain classification models with high sensitivity values, as well as localizing the targets on the handprints (Fig. 1).

Raman HSI and independent component analysis were used to identify traces of a series of explosives on banknotes. In the frame of a real forensic application, this analytical technology was applied to detect ammonium nitrate fuel oil and other explosives in banknotes after the explosion of an automated teller machine [17,18].

Dubroca et al. [19] developed a prototype of an automated system based on differential HSI to identify explosives, in particular 2,4,6-trinitrotoluene (TNT) in luggage. The authors demonstrated that this system is able to detect TNT and other explosives with a good accuracy and the considered device can be easily integrated into the security luggage controls performed in airports.

1.2.2 Biological fluids

Biological evidence, such as body fluids, is regularly found in crime scenes, and successful identification is fundamental for criminal investigations. For these reasons, the characterization of body fluids in crime scenes is another key topic in forensic sciences. In this kind of application, HSI can also represent a valuable tool, allowing the nondestructive and noncontact analysis of forensic evidence, minimizing the risk of contamination [20].

Blood is one of the most common forms of evidence found in violent crime scenes, and in these scenarios the first action taken by investigators is usually to determine whether the stains are made of blood or of other substances that look alike to the naked eye. Visual assessment is subjective and prone to false positives. For this reason, more objective analytical tests were developed to identify bloodstains. The majority of these methods are based on spraying chemical reagents (e.g., luminol) to induce luminescence. However, a

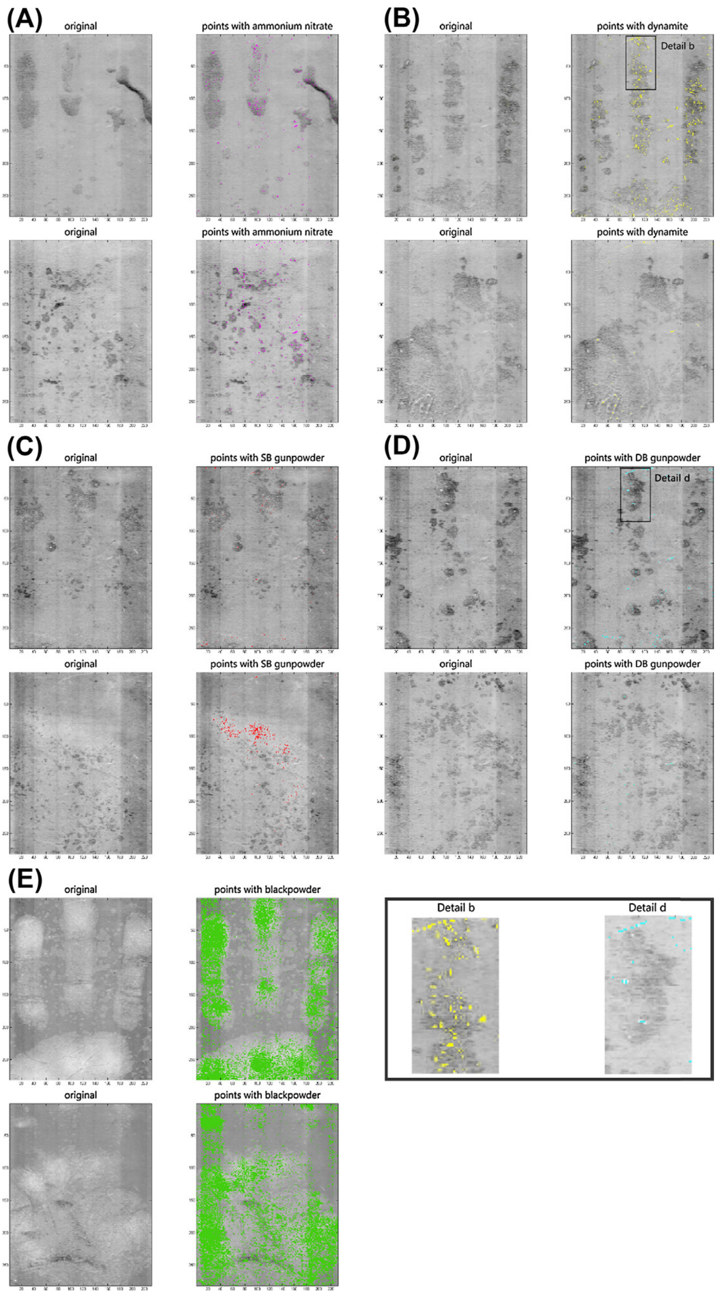

FIGURE 1 Handprint near-infrared false-color hyperspectral images. The presence of explosive residues is highlighted by colored pixels: (A) in *pink* for ammonium nitrate, (B) in *yellow* for dynamite, (C) in *red* for single-base (*SB*) smokeless gunpowder, (D) in *blue* for double-base (*DB*) smokeless gunpowder, and (E) in *green* for black powder. There are 15,402 pixels in a finger sample and 24,821 pixels in a hand palm sample. Enlargements of regions in (B) and (D) are included for clarification. *Adapted with permission from M.Á.F. de la Ossa, J.M. Amigo, C. García-Ruiz, Detection of residues from explosive manipulation by near infrared HSI: a promising forensic tool, Forensic Science International 242 (2014) 228–235.*

completely dark environment is necessary to visualize luminescence and this effect fades quickly [21]. To overcome these drawbacks, HSI in the Vis range has been introduced to identify bloodstains. Hemoglobin has a unique absorption spectrum in the Vis range, which can be used to univocally detect blood [22]. Cadd et al. [23,24] used the specific absorption band of hemoglobin at 415 nm together with other bands in the range 500−600 nm to differentiate bloodstained fingerprints from those stained with commonly encountered red/brown contaminants. Furthermore, Vis−NIR HSI was also shown to be an affective tool to visualize latent traces of bloodstains on different types of fabrics of different colors, including black fabrics [21,25].

The spectrum of hemoglobin changes over time following the oxidation process of hemoglobin. Based on this fact, Vis HSI has also been successfully employed to estimate the age of bloodstains, obtaining satisfactory results considering both fresh bloodstains and bloodstains up to 30 days old [26].

In addition to blood, other body fluids, including semen, vaginal fluid, and urine, are important for crime scene investigations, since these fluids can be further analyzed to identify victims or criminals through DNA tests. In this context, NIR HSI has been evaluated by some researchers to locate body fluids in fabrics and to discriminate the different types of fluids in a mixture [27,28], as shown in Fig. 2.

1.3 Document analysis

Document analysis is an essential task in forensic science to detect document forgery, which consists in a series of possible fraudulent modifications made on documents, such as text obliteration or text addition [29,30]. In this context,

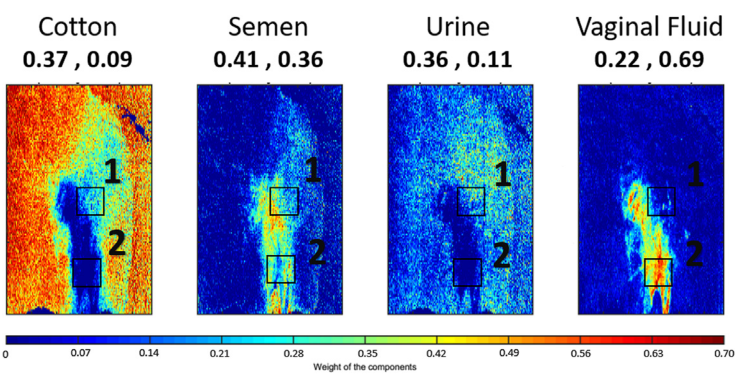

FIGURE 2 Classical least squares (CLS) classification model applied to a mixture of semen and vaginal fluid on cotton fabric. The CLS colored maps for each class (cotton, semen, urine, and vaginal fluid) are displayed. The maximum CLS weight values obtained for each class within the two selected stained regions are indicated above every color map, the first value corresponding to region 1 and the second to region 2. *Adapted with permission from F. Zapata, F.E. Ortega-Ojeda, C. García-Ruiz, Revealing the location of semen, vaginal fluid and urine in stained evidence through near infrared chemical imaging, Talanta 166 (2017) 292−299.*

the use of nondestructive analytical techniques is of fundamental importance since the document evidence should often be preserved for further assessments. HSI has emerged as a powerful analytical technique for the detection of document forgeries, thanks to its ability to provide information about the distribution of organic and inorganic components of a sample, preserving at the same time the physical integrity of the document [31].

A key issue in document analysis is the discrimination of different pen inks to investigate whether a portion of a handwritten text has been somehow altered or modified, with particular attention to differentiating inks of the same color. Indeed, document falsification is often performed using inks that are not distinguishable to the naked eye [32].

Chebda et al. [33] coupled Vis−NIR HSI (470−930 nm) with different chemometric techniques, including hierarchical cluster analysis and spectral angle mapping, to distinguish a set of 35 black pen inks deposited on a paper. In a more recent paper, Silva et al. [30] used NIR HSI (928−2524 nm) and multivariate analysis to identify common forgeries in back checks: the proposed approach allowed one to visualize an obliterated part of the text, identify added or modified numbers, and distinguish crossing lines drawn with print toners or pen inks.

The determination of the order of crossing lines, in particular when they are traced with inks of the same color, is a key topic for the analysis of questioned documents [34]. Braz et al. [35] demonstrated the possibility of using Raman imaging to solve the crossing-lines problem. In this study, crossing lines were drawn on different paper substrates at different times and with several types of blue ink to evaluate the influence of such parameters in determining the correct sequence of crossing. The results were strongly affected by the ink type used to trace the lines due to physical interactions between the inks. In particular, the best results were obtained when the crossing lines were drawn with a gel- and an oil-based ink (Fig. 3).

Not only forgery detection, but also document dating is a relevant issue in forensic science. However, document dating represents one of the hardest problems to solve in forensic analysis, due to the great variability of inks and paper present on the market and to the complexity of the chemical processes undergone during aging [36].

Document dating is generally performed by evaluating the physical−chemical modifications occurring during ink and paper aging processes [29,37]. Several research studies have reported the use of single-point spectroscopic techniques, including Fourier transform infrared spectroscopy, Raman spectroscopy, and UV−Vis spectroscopy, to study the effects of time on printed and handwritten documents, as well as to predict the date of a document [38,39]. The promising results obtained with spectroscopic techniques suggest the possibility of transferring this kind of application also to hyperspectral imagery.

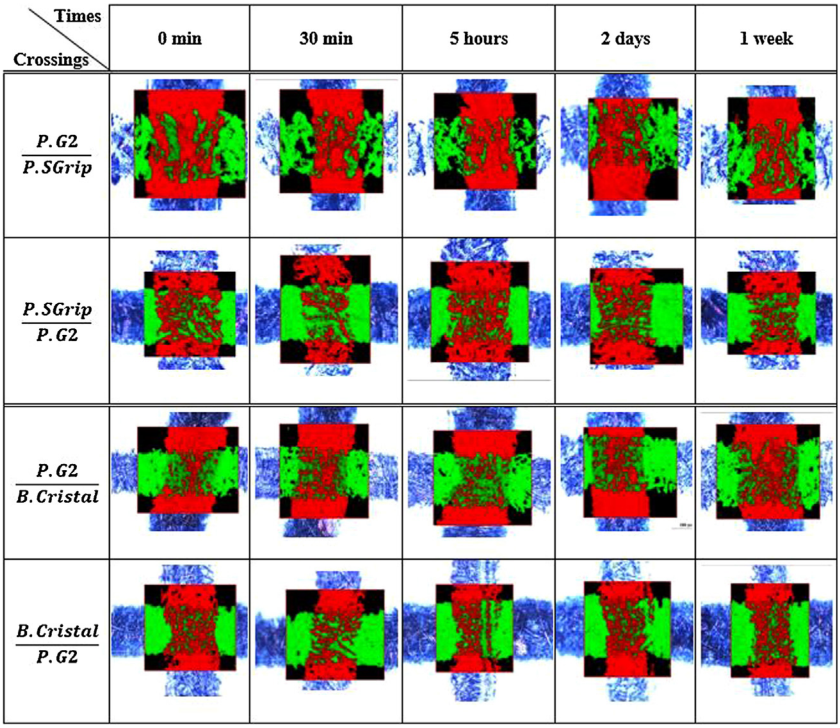

FIGURE 3 False color images obtained from the elaboration of Raman images of crossing lines drawn with gel and oil blue pen inks. Different times separating the application of each line were considered, and the horizontal line (in green) was always applied first. *Adapted with permission from A. Braz, M. López-López, C. García-Ruiz, Raman imaging for determining the sequence of blue pen ink crossings, Forensic Science International 249 (2015) 92–100.*

1.4 Other relevant topics in forensic science

The previous sections investigated the main application areas of HSI in forensic science, including the identification of GSR (Section 1.1), the detection of latent traces (Section 1.2) and document analysis (Section 1.3).

However, many other applications of HSI to forensic studies have been reported in the literature.

Kalasinsky et al. [40] were the first authors to investigate the use of HSI for the identification of drug traces in hairs. Infrared microscopy was used to image the cortex and medulla of hairs derived from normal individuals and a chronic drug abuser of hydromorphone. The analysis of such data allowed them to determine the presence of drugs in hairs and, therefore, to identify drug abusers. Another study by the same authors was focused on evaluating the distribution across hairs of different types of drugs, showing that hydrophilic drugs tend to spread through the cortex of the hair, while lipophilic drugs tend to bind the medulla [41].

In crime cases related to domestic violence and child abuse, the aging of bruises can provide important evidences. Randeberg et al. [42] used Vis–NIR HSI to monitor the development of fresh skin bruises over time in both porcine and human. As the red blood cells disintegrate, hemoglobin degrades to bilirubin. Thanks to the characteristic spectral features of hemoglobin and bilirubin, the authors were able to classify the bruises according aging time.

Forensic entomology is based on the use of insects to estimate the minimum time elapsed since death. In particular, size and/or life stage of insects that generally colonize remains is used to estimate the postmortem interval [43]. Voss et al. [44] demonstrated the possibility of using HSI to assess in a nondestructive manner the age and species of two blowfly puparia: *Calliphora dubia* and *Chrysomya rufifacies*. Spectral profiles of specimens acquired daily were related to morphological changes, allowing the authors to predict pupal age with high accuracy. A broader discussion about the application of HSI in entomology is reported in Section 4.

2. Waste sorting

The current model of production and consumption generates a huge amount of waste, causing severe risks for the environment. To face this critical problem, a different approach to waste management is required, and a desirable trend for the future is represented by the so-called circular economy: transforming end-of-life goods into resources for manufacturing of other products [45].

To support the recycling process, advanced technologies should be employed, in particular in the sorting process, which consists in separating waste objects according to material type and grouping together those that can be somehow transformed for the production of new products. Furthermore, a high level of automation and effective technologies are needed to speed up the sorting phase and make it economically sustainable.

Thanks to its main advantages, HSI has been successfully applied for the sorting of different types of waste, from plastics to electronic and demolition waste. It has to be mentioned that when dealing with hyperspectral data for automated online sorting, the use of adequate data handling and data reduction strategies is of fundamental importance to meet the requirements of the recycling industry [46–49a].

2.1 Waste from electric and electronic equipment

The very fast evolution in the technology of electronic equipment results in a short service life of our electronic devices, which become obsolete in few years [50]. As a consequence, a huge amount of waste from electric and electronic equipment (WEEE) is produced every year, and it is estimated that the waste stream of WEEE will grow strongly in the future [51]. However, it is reasonable to assume that electronic devices and their components entering in the waste stream may still have a value in terms of performance and strength [52].

Generally, electronic devices are made of plastic polymers, including polypropylene (PP), high-impact polystyrene, acrylonitrile butadiene styrene, and polycarbonate, and metals. As a matter of fact, printed circuit boards (PCBs) contain on average of 30% w/w plastic polymers, 30% w/w refractory oxides (mainly silica), and 40% w/w metals, including copper, iron, nickel, silver, and gold [53].

On one hand, the dispersion into the environment of WEEE can represent a major ecological risk due to the presence of toxic elements. PCBs potentially represent an attractive raw material to be recycled for the recovery of plastic polymers and precious metals. The complex and heterogeneous composition of PCBs poses the problem of identifying suitable methods to effectively separate the different components for recycling. Commonly, the input stream of WEEE is subjected to grinding to reduce the dimensions, and subsequently the particles are separated according to density, electric, and magnetic properties [51]. In this context, recycling procedures based on HSI can provide a more comprehensive characterization of the chemical composition of the different components inside WEEE objects, allowing a higher separation rate. In addition, HSI can also be further employed at the end of the recycling process for quality control of recycled materials.

In Palmieri et al. [54] scanning electron microscopy (SEM) was coupled with NIR HSI (1000−2500 nm) to evaluate an efficient and sustainable procedure for recycling both plastic frames and PCBs derived from end-of-life mobile phones. HSI was used to fully characterize the polymer composition of frames and screens, while HSI coupled with SEM allowed the chemical maps of PCBs to be obtained, considering both plastic polymers and metals characterization.

Metal composition of PCBs has been studied using laser-induced breakdown spectroscopy (LIBS) combined with HSI. In Carvalho et al. [55] the elemental distribution of a PCB derived from a mobile phone was visualized from the score maps obtained by applying principal components analysis on a series of spatially resolved LIBS spectra.

A 2017 study conducted on a pilot recycling plant showed the possibility of using a Vis−NIR HSI system for the characterization of fine metal particles derived from shredded WEEE, and the final model implementation allowed a classification accuracy of 95% [56].

2.2 Construction and demolition waste

Construction and demolition waste (C&DW) is made of the solid components derived from waste steams arising from the construction and demolition of buildings and infrastructures (EPA 842/09). To reduce the environmental impact of such type of waste and minimize the exploitation of natural resources associated with the construction sector, increasing attention is devoted to the implementation of recycling strategies for C&DW.

At this writing, the building materials recycling industry is dominated by simple technologies, and sorting processes are generally used to divide light from heavy components through sieves and to separate out steel pieces with magnets [57]. However, new and innovative technologies are necessary to face the problems associated with the recycling of building materials. In this context, HSI may represent an adequate solution for the comprehensive and automated characterization of C&DW streams. Notwithstanding the potential of this technique, sorting of C&DW using HSI technology is a quite young application field.

As a first approach, Kuritcyn et al. [58] evaluated the possibility of combining color images with Vis and NIR spectroscopy to distinguish phenotypically similar building materials, such as concrete, aerated concrete, lightweight concrete, dense brick, and porous brick. This study highlighted the need to combine spatial information provided by color images with spectral information to fully classify those materials with similar chemical compositions but different spatial features.

Subsequently, HSI in the NIR range (1000−1700 nm) was investigated to distinguish aggregates from possible pollutants, including wood, plastic, foam, gypsum, and bricks, obtaining a classification accuracy of 98% [59]. Furthermore, an innovative strategy based on short-wave infrared (SWIR) HSI (1000−2500 nm) was developed to characterize drill-core samples collected from end-of-life concrete [60]. The main goal of this study was to recognize aggregates and mortar paste in concrete and then perform morphological and morphometrical analysis of the aggregates (Fig. 4).

Linß et al. [61] developed a prototype of a sorting system based on NIR hyperspectral sensors to be applied in C&DW recycling. At first, impurities and pollutants are separated from the demolition waste flow, then the different material fractions are separated, with a particular focus on the separation of gypsum attachments and composite particles.

2.3 Plastic waste

Plastic waste is one of the main environmental problems of our period, with 275 million tonnes of plastic waste generated every year. Unfortunately, only a small amount of such waste is recycled, while the remainder is sent to incinerators, disposed of in landfills, or dispersed in the environment, causing pollution of lands and waterways [62].

To overcome the environmental problems associated with plastic waste, there is an increasing awareness of recycling solutions enabling the conversion of end-of-life plastic objects into new marketable products. However, what is commonly referred to as plastic is actually a heterogeneous family of synthetic

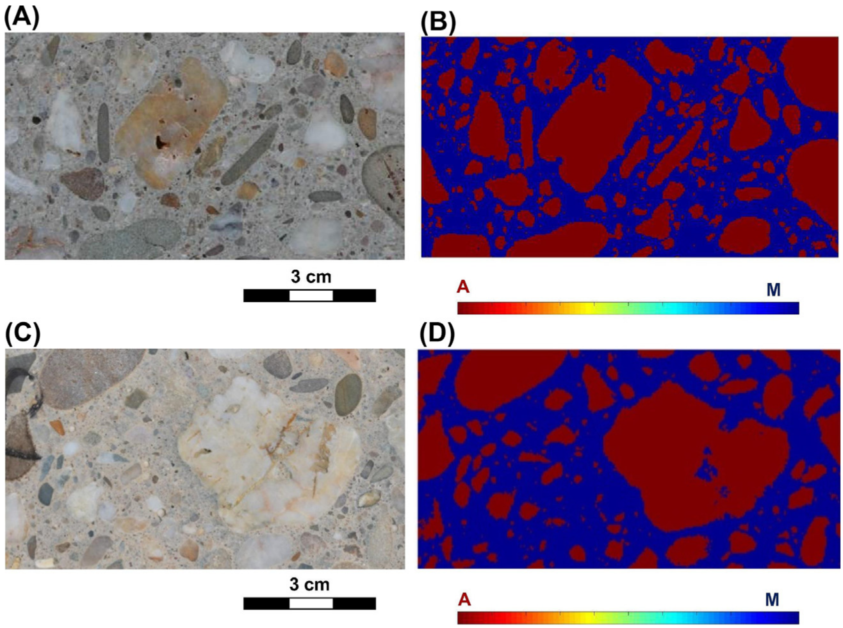

FIGURE 4 RGB images of (A and C) two concrete drill core samples and (B and D) corresponding prediction images obtained with a partial least-squares discriminant analysis classification model. The classes are aggregates (*A*, in red) and mortar (*M*, in blue). *Adapted with permission from G. Bonifazi, R. Palmieri, S. Serranti, Concrete drill core characterization finalized to optimal dismantling and aggregates recovery, Waste Management 60 (2017) 301−310.*

polymers with different physical and chemical properties. Therefore, the correct separation of the different polymers is a key aspect in the recycling process to maintain the quality of the recycled objects.

In this context, NIR HSI is a well-established tool for plastic sorting, meeting also the need for fast methods required by the recycling industry. Indeed, the various plastic polymers have specific spectral fingerprints in the NIR range, and coupling imaging techniques with spectroscopy allows one to simultaneously analyze a large amount of waste objects placed on a conveyor belt in a short time [63].

Due to the relevance of this application field, many research papers have been proposed in which NIR HSI was employed for the discrimination of plastic polymers [64−67].

In the implementation of hyperspectral systems for plastic waste sorting, different aspects should be considered. First, at least six different polymers are commonly used for plastic packaging; therefore it is fundamental to identify suitable classification strategies able to handle a high number of classes. In Bonifazi et al. [68] a hierarchical classification model based on a partial least-

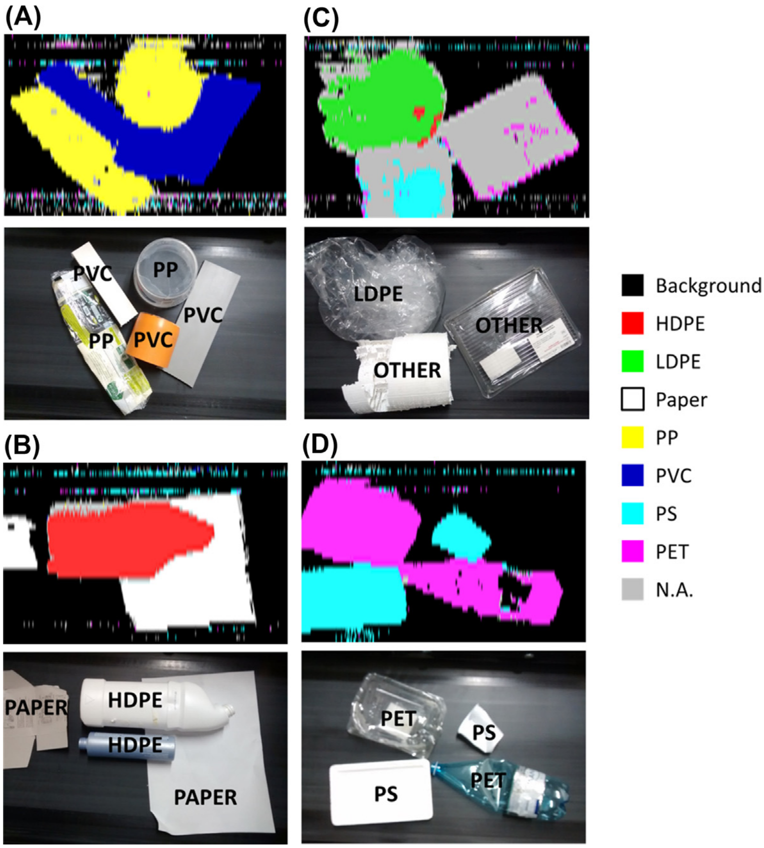

FIGURE 5 (A–D) Four examples of prediction images obtained from a near-infrared hyperspectral system and corresponding RGB images. The imaged objects are made of polypropylene (*PP*), polyvinyl chloride (*PVC*), paper, high-density polyethylene (*HDPE*), low-density polyethylene (*LDPE*), polyethylene terephthalate (*PET*), polystyrene (*PS*), and other plastic polymers (*OTHER*; *N.A.*). *Adapted with permission from R. Calvini, G. Orlandi, G. Foca A. Ulrici, Development of a classification algorithm for efficient handling of multiple classes in sorting systems based on HSI, Journal of Spectral Imaging 7 (2018) a13.*

squares discriminant analysis algorithm has been successfully implemented to discriminate polymer flakes of plastic waste. Calvini et al. [63] used an industrial prototype of a hyperspectral-based sorting system to discriminate the more common plastic polymers used in packaging (Fig. 5). In this context, the authors developed a specific algorithm, which includes a rejection option allowing one to identify possible foreign materials. Indeed, it is not possible to completely control the materials present in the input stream of plastic waste and, for this reason, an important task is to identify foreign objects and possible contaminants.

Another issue related to hyperspectral-based sorting systems for plastic waste is the huge amount of data that have to be processed in a short time. A possible solution is the identification of relevant spectral bands specific of each polymer to reduce the number of spectral channels considered [63,69].

Furthermore, not only the separation of the different polymers is important, but there is also the need for characterizing polymers belonging to the same class according to additional properties; for example, it is necessary to differentiate polyethylene (PE) objects in high-density PE (HDPE) and low-density PE (LDPE). In De Biasio et al. [70] spectral feature selection was applied to classify PE objects into HDPE and LDPE classes, while PP objects were sorted according to melting point. Moreover, Amigo et al. [46,71] evaluated the possibility of using NIR HSI to discriminate different types of plastics (e.g., acrylonitrile−butadiene−styrene and polystyrene) according to the flame retardants used as additives.

3. Archaeology

Archaeology deals with the study of human history through the excavation of old sites and the analysis of ancient artifacts or other physical remains. HSI is emerging as a powerful discovery and analytical tool for archaeologists. Satellite or airborne images are used to cover large areas to identify new interesting excavation sites or to support archaeologists in investigating the architecture of ancient settlements. Moreover, hyperspectral systems are used for the noninvasive analysis of artifacts and physical remains. HSI can be employed directly in situ to perform preservation studies on wall paintings, or it can constitute a useful tool at the laboratory scale to analyze fragile archaeological remains.

3.1 Archaeological remote sensing

Satellite and airborne HSI has positively contributed to archaeological research, representing a complementary tool supporting excavation fieldwork. In this context, HSI has been mainly applied for the retrieval of buried archaeological structures, to provide valuable information to field archaeologist for the identification of proper excavation sites. Basically, the presence of buried structures can be related to anomalies in the biophysical information contained in the images, which in turn are generally ascribable to differences in vegetation growth and/or soil humidity [72].

Therefore, hyperspectral image acquisition and analysis are strongly connected with field excavation and archaeological surveys (Fig. 6). Remote sensing allows one to cover large areas to identify places of interest. Then, the archaeologist can focus fieldwork surveys on specific areas, but he or she may also need additional images or a more targeted image analysis to further refine the area for subsequent excavation. Moreover, even if the area of interest has

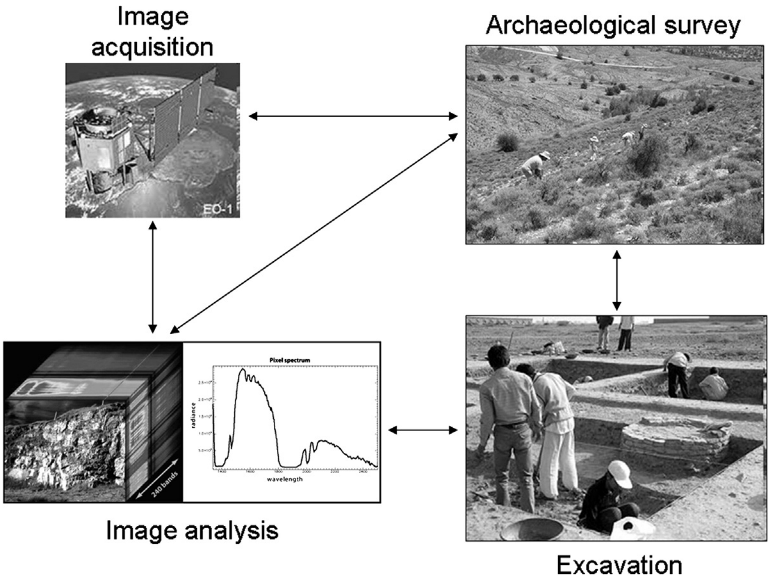

FIGURE 6 Relationships between remote sensing and fieldwork operations. *Adapted with permission from S.H. Savage, T.E. Levy, I.W. Jones, Prospects and problems in the use of hyperspectral imagery for archaeological remote sensing: a case study from the Faynan copper mining district, Jordan, Journal of Archaeological Science. 39 (2), (2012) 407–420.*

already been investigated by many field surveys and excavations, hyperspectral image analysis allows one to observe the same area under a different point of view, producing unexpected results and suggesting new avenues of inquiry [73].

In Kwong et al. [74] satellite hyperspectral images covering an area of approximately 30,000 km^2 of the Oaxaca Valley (Oaxaca, Mexico) were analyzed to relate soil and vegetation type with ancient settlements and trade systems of the Zapotec civilization.

Cavalli et al. [75] compared different remote-sensing systems working in different regions of the electromagnetic spectrum for their potential in revealing anomalies related to buried archaeological structures. The results of this study showed that the Vis–NIR region is more effective in indicating the presence of buried structures in those areas where vegetation cover is dominant, while SWIR HSI is more suitable for those situations where soil cover is more relevant.

Alexakis et al. [76] used remote sensing to detect particular Neolithic settlements, called *magoules*, in Thessaly, a region in Greece where hundreds of these settlements were established from the Early Neolithic period until the Bronze Age. Several airborne imagery systems with different spatial and spectral resolutions were used for this study. The authors pointed out the need for an adequate spectral and spatial resolution for the specific target under investigation. Spatial resolution is important to correctly outline the features of interest, while optimal spectral resolution allows one to distinguish the spectral profile of the archaeological settlements from the spectral profile of the surroundings. In the specific case under investigation, optimal results were obtained by merging the high spectral abilities of the Hyperion system (Northrop Grumman Corp., USA) with the high-resolution images of the Ikonos system (DigitalGlobe, USA).

Notwithstanding the great advantages of airborne HSI in archaeological surveys, there are still some limitations mainly related to the analysis of the images. Indeed, each hyperspectral image contains a large number of spectral bands with high data redundancy and a low signal-to-noise ratio due to different atmospheric conditions. To simplify the analysis of such type of images, Atzberger et al. [77] developed a specific graphical user interface working under MATLAB environment (MathWorks, USA) and named ARCTICS (Archaeological Toolbox for Imaging Spectroscopy). This toolbox contains specific algorithms for filtering, enhancing, and visualizing the relevant information contained in hyperspectral images with a focus on archaeological applications.

3.2 Characterization of archaeological artifacts

Archaeological artifacts generally have a heterogeneous composition and they are a fragile sample that should be preserved over time. As a noninvasive analytical technique, HSI is a promising method of investigation in the characterization of archaeological artifacts, including ancient wall paintings, manuscripts, and pottery, among others [77a,b].

Wall paintings contain rich historical and artistic information, reflecting the cultural background and the level of science and technology of the period in which they were created. HSI is generally used to perform a noninvasive identification of the pictorial materials constituting the painting, i.e., pigments, dyes, and preparation layer.

Capobianco et al. [78] used a benchtop HSI system working in the SWIR range (1000–2500 nm) to identify and map the different pigments present on the surface of fragments derived from an ancient Roman wall painting. Based on these results, the authors highlighted the potential of this technique for the in situ characterization of whole murals.

Wall paintings are strongly subject to deterioration caused by weathering, erosion, or vandalism. Over time, damages such as cracking and peeling gradually appear on wall paintings, causing their degradation. In this context, HSI can represent a valuable diagnostic tool to rapidly and easily identify damaged parts of wall paintings. In Sun et al. [79] NIR HSI allowed the evaluation of the flaking degree of the ancient murals in the Mogao grottoes (Dunhuang Cultural Research, China). Classification models were calculated to discriminate among four levels of flaking: normal, slight, moderate, and severe. In this case, hyperspectral image acquisition was performed directly onsite using a line-scanning acquisition system. Pan et al. [80] demonstrated the possibility of combining Vis−NIR and SWIR HSI to reveal faded mural patterns using as an example the faded leaf-like patterns in a typical Tang dynasty tomb in China.

The study of ancient manuscripts is of utmost importance for archaeologists, since ancient documents represent relevant evidence of past civilizations. Manuscripts are typically fragile artifacts prone to degradation. Indeed, they are written on soft and perishable materials such as leather or paper. Furthermore, the inks tend to fade over time or to become indistinguishable from dark or aged writing surfaces. The noninvasive analysis of ancient manuscripts through HSI is becoming an essential tool for archaeologists, allowing them to face typical problems occurring in manuscript analysis, including the chemical characterization of black and colored inks and the visualization of faded inks [81]. Therefore, the interpretation of the outcomes provided by hyperspectral data is a valid support to archaeologists in the assessment of the state of conservation and in the validation of historical hypothesis.

Catelli et al. [82] used Vis−NIR HSI combined with a chemometric approach to map the various colorants used in a fragment of an illuminated manuscript.

In Pouyet et al. [83], Vis HSI and synchrotron-based macro-X-ray fluorescence were combined to reveal the hidden text of a degraded illuminated manuscript of the 6th century. This study allowed the identification of the different inks and the visualization of their sequence of use, revealing also the presence of ruled guidelines used to align the text and of two types of comments to the main text.

HSI can also be used to assess the state of preservation of a manuscript to develop targeted approaches for its conservation. Indeed, over time documents tend to show evidence of deterioration, including, for example, paper yellowing or the presence of stains. Goltz et al. [84] used Vis HSI (420−720 nm) for the visualization and quantitative assessment of staining in two different historical documents: a handmade manuscript and a machine-made paper. The authors highlighted the ability of Vis HSI to enhance features not visible to the naked eye, such as light stains or texts covered by dark stains. Furthermore, the quantification of the extent of the stains could allow one to monitor the amount of staining over time to evaluate the effects of storage conditions and prevent further degradations.

4. Entomology

Entomology, the branch of zoology that studies insects, can represent a captivating field of application of HSI. Entomology research studies have a wide range of targets, including the identification of insect species, the evaluation of insect adaption to external stress agents, and the study of insect infestations to identify optimal pest management procedures. In this context, HSI is emerging as a powerful analytical technique allowing analysis of insects or infested samples in a noncontact and nondestructive manner.

The most widespread application of HSI to insect identification is related to precision agriculture, where hyperspectral or multispectral cameras are used for a fast screening of fields to identify infested crops or plants. The increasing awareness about risks associated with invasive insect species resulted in the need for novel technologies able to speed up the inspection procedures of import/export goods. Acknowledging that this is a major application, here we are focusing on the applications that involve benchtop instruments.

A key aspect of these inspection procedures is represented by insect identification and, in this context, benchtop HSI can help in developing control procedures with short processing times and a high level of automation. Several research studies successfully reported the use of HSI to classify a wide range of insect species. As an example, Klarica et al. [85] used NIR HSI to discriminate two cryptic ant species: *Tetramorium caespitum* and *Tetramorium impurum.* These two ant species are defined as cryptic since they have very similar morphological features and they can be distinguished only with molecular genetics or high-precision morphometrics. In this study, NIR HSI allowed the authors to obtain a classification accuracy equal to 98.8%, showing the great potential of this technique for fast classification of cryptic insect species.

Using a Vis−NIR HSI system, Nansen et al. [86] classified three species of egg parasitoids belonging to the genus *Trichogramma*: *Trichogramma galloi*, *Trichogramma pretiosum*, and *Trichogramma atopovirilia*. Due to their small size (adult specimens are less than 1 mm length) and similar morphological features, the classification of these species is time consuming and requires a high level of technical experience. HSI allowed the authors to obtain satisfactory classification results not only on adult specimens, but also considering the reflectance profiles of host eggs parasitized by the three species of *Trichogramma*.

Recently, Wang et al. [87] compared Vis−NIR HSI (411−870 nm) with a combined approach of alpha taxonomy and mitochondrial DNA to classify seven species of evacanthine leafhoppers (Hemiptera: Cicadellidae). This study demonstrated that HSI was able to provide a classification accuracy of about 91.3% for those species that could be distinguished on the basis of alpha taxonomy and mitochondrial DNA.

The identification of possible insect infestations is one of the key aspects of safety and quality control procedures in the food industry. To this aim, NIR and thermal imaging have been widely used to detect insect infestations in food products, including wheat kernels [88−90], peas [91], and soy beans [92], among others [93].

An emerging application of benchtop hyperspectral instrumentations deals with physiologic and phenomic studies of insects. Concerning physiologic studies, synchrotron X-ray imaging increased the current knowledge of physiological mechanisms of insects [94]; indeed, this technology was used to study the behavior of insect flight muscles [95,96]. Furthermore, synchrotron X-ray imaging has also been employed to locate and monitor chemical modifications of potential toxic elements. As an example, using this technology, Mogren et al. [97] studied the localization and biotransformation of arsenic in two insect species: the harlequin fly (*Chironomus riparius*) and the mosquito *Culex tarsalis*.

Phenomic studies evaluate the adaptation of insects in response to environmental factors, such as temperature changes or exposure to killing agents. Coupling ^1H magnetic resonance imaging and spectroscopy, Mietchen et al. [98] studied the mechanisms embraced by insect larvae to adapt to cold temperatures. Nansen et al. [99] used Vis−NIR HSI (434−876 nm) to study changes in individuals belonging to two beetle species exposed to killing agents. Time series hyperspectral images of both exposed and unexposed specimens were acquired over a period of about 100 h and for both beetle species it was possible to identify modifications in the reflectance profiles ascribable to the exposure to killing agents.

5. Conclusions and perspectives

Different fields have different needs in what concerns instrumentation and speed. HSI and MSI cameras have widely demonstrated their adaptability in many different situations. Nowadays there is a wide market that offers benchtop instruments working at full spectral range to filter-based cameras working with a limited amount of wavelengths. Indeed, the hyperspectral solution is normally a tailored solution with respect to the type of camera and algorithm needed to solve a specific problem. This versatility, and the growing demand for faster and more accurate hyperspectral devices, makes it possible that HSI and MSI will take part in more and more applications.

In this chapter we have reviewed some of the applications in which we believe that HSI and MSI play, and will play, an important role.

Forensic science is in need of accurate hyperspectral cameras, accurate in both spectral and spatial resolution. Robust and reliable databases are needed, together with powerful algorithms, to find traces of elements (e.g., drugs or explosives) in sometimes harsh environments. Acknowledging that HSI and MSI should be used in a deductive manner, the possibility of scanning large areas to find those traces opens a totally new spectrum of possibilities. Moreover, the add-on of portability is a great advantage, since crime scenes will be able to be studied without the need for direct human intervention on the samples (e.g., no need to use luminol).

Recycling waste, nowadays, is a question of speed. More and more waste passes by conveyor belts where it needs to be sorted at high speed. The great advantage is that a good spatial resolution is not normally needed. Moreover, with the new variable selection methods, many types of waste can be separated by using fast MSI cameras with dedicated wavelengths. Nevertheless, new issues are arising. For instance, there is a need in plastic sorting to localize those plastics that contain flame retardant. Along this line, several projects are being developed. But still there are many aspects that can be improved (like the type and concentration of the flame retardant, colorants, metallic influences, etc.).

Archaeology is a branch of science that is using a large collection of different HSI and MSI cameras, depending on the type of problem to be solved, from remote-sensing cameras for detecting settlements up to benchtop instruments to detect pigments in ancient instruments. Here time is not a problem, but high spectral and spatial resolutions are needed. In contrast, entomology needs high spatial and spectral resolution together with speed, since controlling the growth of pests is fundamental in, for instance, precision agriculture. Furthermore, an intriguing future perspective is represented by the use of benchtop HSI systems as a support tool for entomologists in systematic and phenomic studies of insects.

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