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Circular and sustainable space: Findings from hyperspectral imaging

N. Aversano [c], G. Bonifazi [a], I. D'Adamo [b], R. Palmieri [a,*], S. Serranti [a], A. Simone [c]

[a] *Department of Chemical Engineering, Materials and Environment, Sapienza University of Rome, 00184, Rome, Italy*
[b] *Department of Computer, Control and Management Engineering, Sapienza University of Rome, 00185, Rome, Italy*
[c] *Thales Alenia Space Italia, S.da Antica di Collegno, 253-10143, Torino, Italy*

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ABSTRACT

Clean production and the ecological transition pose significant challenges for international space organizations, which are developing new strategies for recycling space waste products within a circular economy model. Successful recycling initiatives, which could encompass all or only parts of space waste management, would facilitate the reuse of materials that would otherwise be discarded. The present study aimed at testing a method for the identification and categorization of space waste to facilitate the definition of effective sorting and recycling operations in space. In more detail, the study investigated the potential of a sustainable, low-cost method based on hyperspectral imaging (HSI), employing HSI sensors operating in two spectral ranges—-shortwave infrared (SWIR) and near-infrared (NIR)—to develop a classification model capable of identifying and sorting space waste for recycling. The findings demonstrate the advantages of using HSI techniques to identify, recognize, and classify various materials, thereby presenting a viable approach aligned with the circular model. Moreover, the proposed approach is non-invasive and non-destructive, eliminating the need for chemicals that could harm the environment. The technique may enable the differentiation of potentially valuable space waste from pollutants, contributing to sustainable waste management and the circular economy.

1. Introduction

Cleaner production, in support of the sustainable transition, is a crucial societal goal (Almeida et al., 2017). To achieve this goal, the three dimensions of sustainability must be addressed (Giannetti et al., 2022, 2023), following a pragmatic approach involving all stakeholders, including younger generations (D'Adamo et al., 2024a) with a key role played by sustainable education (Inglezakis et al., 2023). On their part, companies must consider and appropriately incorporate concepts such as clean production, carbon markets, labor relations, and the circular economy, into their strategies (Silva et al., 2024). In particular, the development of a circular economy model may support the sustainability transition through the efficient utilization of physical and economic resources (Lombardi et al., 2021). The development of a circular economy model is based on competitiveness and innovation with resource management based on circularity so as not to generate geopolitical dependencies related to imported raw materials (D'Adamo et al., 2024b). In this regard, collaboration between businesses and technology developers allows for environmental and economic benefits even in the short term (Khan and Khurshid, 2024). It emerges in this regard that change is driven by the availability of employee skills and organizational capabilities. These aspects should be paid attention to in circular start-ups (Straub et al., 2023). New in-house capabilities along the value chain are needed to reduce costs, increase productivity, encourage brands to adopt green practices and meet green consumer expectations (Voukkali et al., 2023).

In the unique context of space exploration, the rapid proliferation of orbital debris poses a significant challenge to sustainability, emphasizing the urgent need for waste mitigation strategies aligned with the circular economy model (Leonard and Williams, 2023). The Advanced Exploration Systems logistics reduction project at NASA aims at developing technologies to address waste-related challenges and reducing resource expenses associated with space missions (McKinley et al., 2023). In more detail, reducing the costs associated with the supply of resources from Earth is essential, alongside consideration of the ethical implications related to space waste production and the preservation of extraterrestrial environments. Loop-closure, referring to the repurposing and recycling of resources to advance the circular economy, could significantly enhance space exploration sustainability (Santomartino et al., 2023). Some analyses show that emissions associated with

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* Corresponding author.
E-mail address: roberta.palmieri@uniroma1.it (R. Palmieri).

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launches and re-entries have no impact on atmospheric density below 500 km (Perks et al., 2024).

Current legislation and guidelines for space sustainability are deficient in several aspects, allowing the space sector to continue operating without consequences for various negligent actions (Wilson and Vasile, 2023). Some authors have discussed how an unsustainable orbital environment is a result of an antiquated regulatory framework (Martin-Lawson et al., 2024). This has resulted in overloaded orbits and the accumulation of space waste, compromising long-term space accessibility (Wilson et al., 2022). Therefore, material classification is essential to select appropriate systems and machines to deal with this waste (e.g., shredders, classifiers, separators, extruders), as well as to develop recycling process plans ahead of missions (Allwood, 2024).

One of the most challenging aspects of space waste mitigation and recycling is the quick, reliable, efficient, affordable, non-invasive, and non-destructive analysis of different solid waste typologies. Where this is possible, waste may be further explored with respect to its potential for recycling and reuse directly in space (e.g., on spacecrafts). For instance, certain polymers could be recycled into "wires" for 3D printers to produce small prototypes or parts for experiments or functional spacecraft elements.

Over the past decades, use of hyperspectral imaging (HSI) in the field of waste recycling has significantly increased, enabling the identification of different materials based on their unique spectral signatures (Calvini et al., 2019; Palmieri et al., 2023). HSI is a non-destructive technique that gathers information from a wide range of the electromagnetic spectrum and stores spectral data in a hyperspectral image cube (i.e., a three-dimensional data structure with two spatial dimensions and one spectral dimension). Thus, the technique can be used to distinguish different materials based on their reflectance spectra, which unmistakably reflect their compositions due to the presence of specific chemical bonds (e.g., O–H, N–H, C–H, S–H) (Geladi et al., 2007; Hyvarinen et al., 1998). Each pixel in a hypercube represents a spectrum. Consequently, datasets containing the entire spectrum at each location in a spatial array are known as hyperspectral images.

HSI approaches enable the quality of recycled materials to be monitored, helping to ensure their compliance with industry standards (Bonifazi et al., 2019, 2021). In recent years, various HSI approaches have been developed for efficient plastic recycling (Neo et al., 2022; Zheng et al., 2018), construction management and waste demolition (Serranti et al., 2015), and electrical and electronic waste handling (Bonifazi et al., 2020; Palmieri et al., 2014). The literature demonstrates that application of HSI in the waste industry can significantly impact the effectiveness of various circular process phases (e.g., material selection, component identification, quality control). Furthermore, sorting process efficiency may increase through the automation of waste material identification and selection, thereby enhancing the purity of the recycled materials. In addition, when HSI is utilized in place of traditional manual sorting processes, labor costs lower and throughput rates may increase (Tao et al., 2023). Finally, HSI approaches may also optimize energy consumption in both manufacturing and end-of-life processes, following the principles of industrial symbiosis (Agudo et al., 2023; Núñez and Perez-Castillo, 2023).

The literature highlights that space waste management should be approached with a circular economy approach (Leonard and Williams, 2023; Wilson and Vasile, 2023). It emerges a gap in the literature with respect to the identification of environmentally friendly and pragmatic methods offering real and beneficial solutions for civil society. To this end, the differentiation of space waste materials is needed to determine the most appropriate tools and processes for end-of-life treatment. The present study aimed at exploring the feasibility of HSI techniques for this purpose. In more detail, the research investigated the potential of using HSI to manage waste from space activities and evaluate the sustainable and circular benefits associated with this waste. Notably, the HSI sensing architecture has a low environmental impact, and use of HSI for “off-line” and “at-line” analyses does not require chemicals. Furthermore, HSI analyses can occur "in-line" (on a laboratory scale) and "on-line" (on a processing line scale), promoting a comprehensive and sustainable approach.

The remainder of the paper is structured as follows. Section 2 offers a review of the literature, while Section 3 describes the methodology, the techniques used, and the relevant samples analyzed. Following this, Section 4 presents the results, and Section 5 subsequently discusses, compares, and explores these results. Finally, Section 6 offers concluding remarks.

2. Context and literature analysis

Following the historic launch of the first man-made satellite, Sputnik I, into orbit on October 4, 1957, the United States and several other countries swiftly joined the space race with a series of subsequent launches (Buchs, 2020; Mejía-Kaiser, 2020). Concurrently with the progression of space missions, the volume of waste generated as a byproduct of these operations rose significantly, necessitating effective waste space management strategies. Therefore, while long-duration space missions require careful attention to ensure that crews are equipped with the necessary resources for survival and well-being, management of the generated waste is equally crucial (Linne et al., 2014).

On a daily basis, spacecrafts generate a range of material wastes, including crew biological products (i.e., carbon dioxide, water, organic waste) and solid and liquid wastes. The International Space Station (ISS) diligently manages solid waste, which includes items such as packaging materials, used clothing, and other non-recyclable items (Anih, 2022). During a yearlong mission, four astronauts can produce up to 2500 kg of waste (Brinkert et al., 2023). This trash not only occupies valuable space but also poses safety risks to the crew due to potential biological and physical hazards. Currently, the majority of the waste generated is not recycled but is instead disposed of. The ISS crew compacts solid waste, wraps it in duct tape, and stores it until the next supply vehicle arrives (Agrella and Smith, 1991; Jiang et al., 2023). The waste is then placed into the supply vehicle, which is released and burnt up in the Earth’s atmosphere. However, as this approach is not feasible for missions located farther from Earth (i.e., those at an Earth-moon Liberation point or in transit to Mars), alternative solutions are needed. Therefore, over recent years, scientists have been exploring the possibility of directly gathering and recycling waste materials in space.

The United Nations Committee on the Peaceful Uses of Outer Space has established recommendations for the Long-term Sustainability of Outer Space Activities (Brachet, 2012). This effort aims at promoting space sustainability, defined as the ability to pursue space operations indefinitely while ensuring fair access to the benefits of exploration and use of space for peaceful purposes. Thus, the goal is to preserve the space environment for future generations while meeting current needs.

Space waste management is a critical component of space sustainability. The 2030 Agenda for Sustainable Development highlights that space operations should minimize their impacts on both Earth and the space environment. Moreover, the "Space4SDGs" project indicated that all 17 Sustainable Development Goals (SDGs) have a positive impact on space. Of the 169 targets, 65 benefit from the European Global Navigation Satellite System (GNSS) and Copernicus missions, alone. However, the increasing use of space poses significant risks, including traffic congestion, collisions, and the creation of additional waste in orbit. Accumulating debris in space can render the space environment inaccessible for extended periods, presenting a serious and urgent concern (Barentine et al., 2023). If not addressed promptly, this situation could effectively halt industry operations (Liu et al., 2023).

Space waste comprises various materials, including metals (e.g., aluminum, titanium, steel) associated with the structural components of spacecraft, composites such as carbon fiber-reinforced polymers, ceramic debris from heat shields, and specialized paints and coatings used for radiation protection (Alami et al., 2023). Moreover, some spacecraft components (e.g., wiring, insulation) and packaging (e.g., bags, boxes) are made of plastics, which are lightweight and sufficiently durable to withstand space conditions. The effective handling of end-of-life plastics and other materials in space is becoming a significant priority for NASA and other international space agencies, with the aim of reducing waste by reusing materials that would otherwise be discarded (Hall, 2021). Thus, ongoing research and technological developments are focused on the direct improvement of waste management.

The literature proposes various methods to enhance recycling capabilities and reduce reliance on the Earth for resupply (Ailor, 2022; Makaya et al., 2023). Two viable options that may balance financial advantages and technical development are reuse and recycling (Letellier and Lizy-Destrez, 2022; Paladini et al., 2021). To establish mission requirements for the design and implementation of recycling processes, material categorization is essential. This is because the classification of circular economy models is complex and varies according to different waste categories (De Pascale et al., 2021) and end-of-life management modes (D'Adamo and Rosa, 2016). Additionally, material selection is crucial to ensure durability and reduce environmental impact (Mesa et al., 2020), including in the space environment (Mark and Kamath, 2019). Consequently, material categorization represents more than just preliminary work; rather, it represents the cornerstone upon which customized recycling processes must be built in order to select and design specialized equipment (e.g., shredders, classifiers, separators, extruders) that meet space mission requirements.

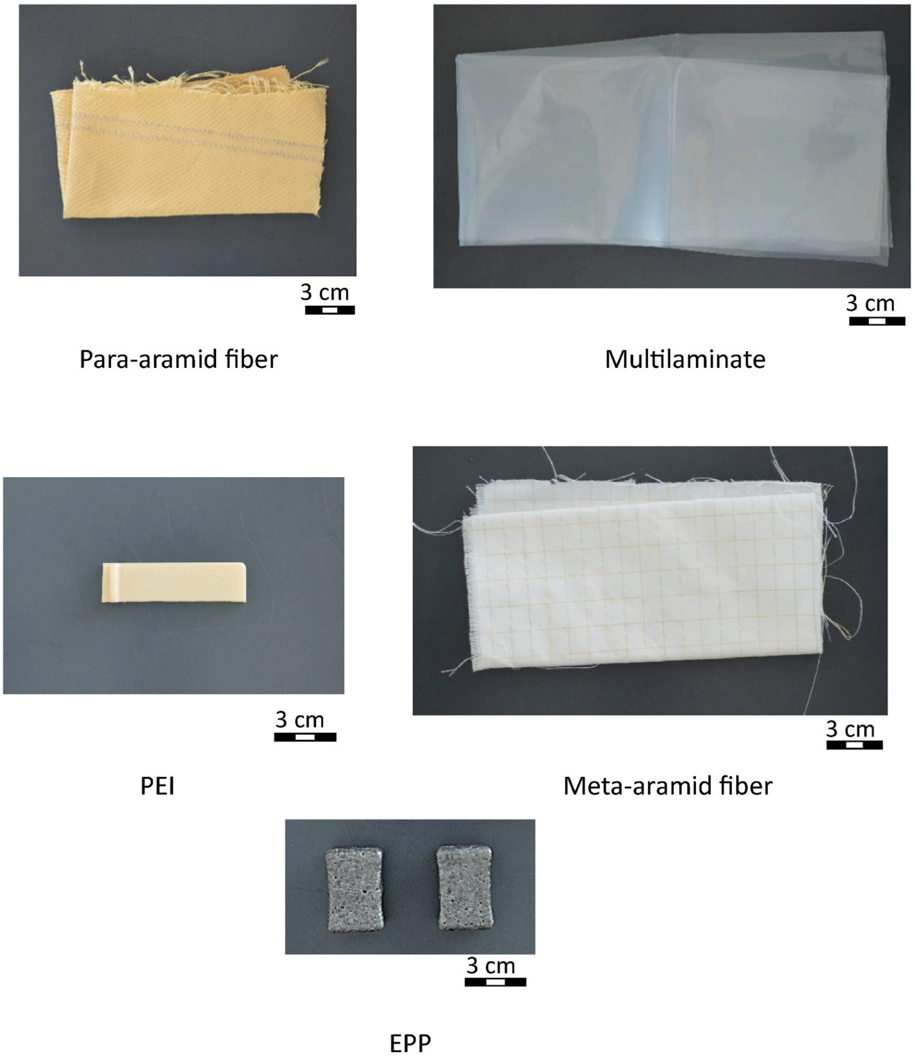
The fast, reliable, low-cost, and non-destructive analysis of solid waste and end-of-life materials poses a significant challenge in space (Bonifazi et al., 2022), which hosts a wide array of end-of-life products. An automated and efficient waste item identification and sorting system could result in recycled materials of the highest purity. HIS represents a promising sustainable approach in this direction (Bonifazi et al., 2019; Palmieri et al., 2023) that would protect extraterrestrial habitats.

3. Materials and methods

The present study, based on a collaboration between Sapienza University of Rome and the company Thales Alenia Space Italia, aimed at developing closed-loop, sustainable, and inclusive factories and processes for managing space waste. In this regard, HSI was considered over other techniques due to its capacity for detailed, non-destructive, real-time material analysis. This method ensures the accurate identification of valuable materials, the detection of contaminants, and the assessment of degradation, all of which are crucial for ensuring the sustainability and efficiency of space missions and space waste management in a circular perspective.

3.1. Analyzed samples

Analyses were conducted on samples supplied by Thales Alenia



Para-aramid fiber

Multilaminate

PEI

Meta-aramid fiber

EPP

Fig. 1. Digital images of the analyzed samples used for the classification model building.

Space Italia, comprised of materials that are widely utilized in space applications. These materials include foam, technical textiles, multilayer structures, and techno-polymers that, at the end of their lifespan, may transform into space waste in the form of scraps. Five samples were analyzed, as shown in Fig. 1. These samples consisted of para-aramid fiber (i.e., protective material), meta-aramid fiber (i.e., textiles/bags), multilaminate (i.e., food packaging), polyetherimide (PEI; i.e., high-performance flame-retardant thermoplastic), and expanded polypropylene (EPP; i.e., packaging).

Para-aramid (e.g., Kevlar) and meta-aramid (e.g., Nomex) fibers are widely utilized in the aerospace sector due to their exceptional mechanical and thermal properties, which enhance the performance, safety, and reliability of aerospace systems. Their unique properties, which include high strength, thermal stability, and resistance to impact and fire, make them indispensable in the aerospace industry. Multilaminate materials (e.g., polyamide/polyethylene with an ethylene vinyl alcohol barrier) are used for packaging food preservation for long-duration space missions. These materials maintain the integrity and freshness of food by providing an effective barrier against the harsh space environment. PEI is noted for its excellent mechanical strength, heat resistance, flame retardancy, dimensional stability, electrical insulating properties, and chemical resistance. It is used in spacecraft components that require high strength, thermal stability, and flame resistance (e.g., structural parts, electrical insulators, and components that must withstand the high temperatures and radiation in space). EPP is a lightweight, durable, flexible foam with excellent energy absorption, impact resistance, and thermal insulation properties. It is also recyclable and resistant to chemicals and moisture. These properties make it ideal for the packaging and protection of sensitive equipment during launch and transport. Its excellent energy absorption and impact resistance help to safeguard instruments and other critical components from the vibrations and shocks experienced during launch and landing. Additionally, its thermal insulation properties are valuable for protecting components from temperature extremes.

From the material samples, fragments were cut to build experimental set-ups for the identification, recognition, and classification of different categories in the acquired hyperspectral images.

3.2. *Hyperspectral imaging systems*

Two acquisition platforms, operating in distinct spectral ranges, were utilized to acquire hyperspectral images in the near infrared (NIR: 1000–1700 nm) and short wave infrared (SWIR: 1000–2500 nm) regions, respectively (Fig. 2). The NIR Spectral Camera™ (Specim, Finland), equipped with an ImSpector N17E™ (SPECIM Ltd, Finland) imaging spectrograph, operated in the NIR using Spectral Scanner™ software for spectra acquisition and collection. These acquisitions took place at the Laboratory of Raw Materials in Latina, within the Department of Chemical Engineering, Materials & Environment (Sapienza University of Rome). The HSI platforms employed were configured with a conveyor belt that transported the particles/materials. SWIR acquisitions were conducted at the Raw Material Lab of the same department. The SisuCHEMA XL™ Chemical Imaging workstation, manufactured by SPECIM Ltd in Finland, equipped with Chemadaq™ software, was used for the spectra acquisition and collection.

Both devices function as push-broom line scan cameras, capturing spectral information for each pixel along the scanned line. The transmission diffraction grating and optics ensure high light throughput, maintaining a high quality, distortion-free image. In the present study, samples were scanned line by line during image acquisition. Calibration for black and white references was manually performed for the Specim ImSpector™ N17E and automatically executed for the Specim SISUChema XL™.

To calibrate acquisition in the NIR, two images—one for the black reference and one for the white reference—were recorded. To capture the black image, the light source was turned off and the camera lens was covered with its cap. To obtain the white image, an NPL Spectralone® (ProLite Technology, Innovation Centre, Cranfield University, Milton

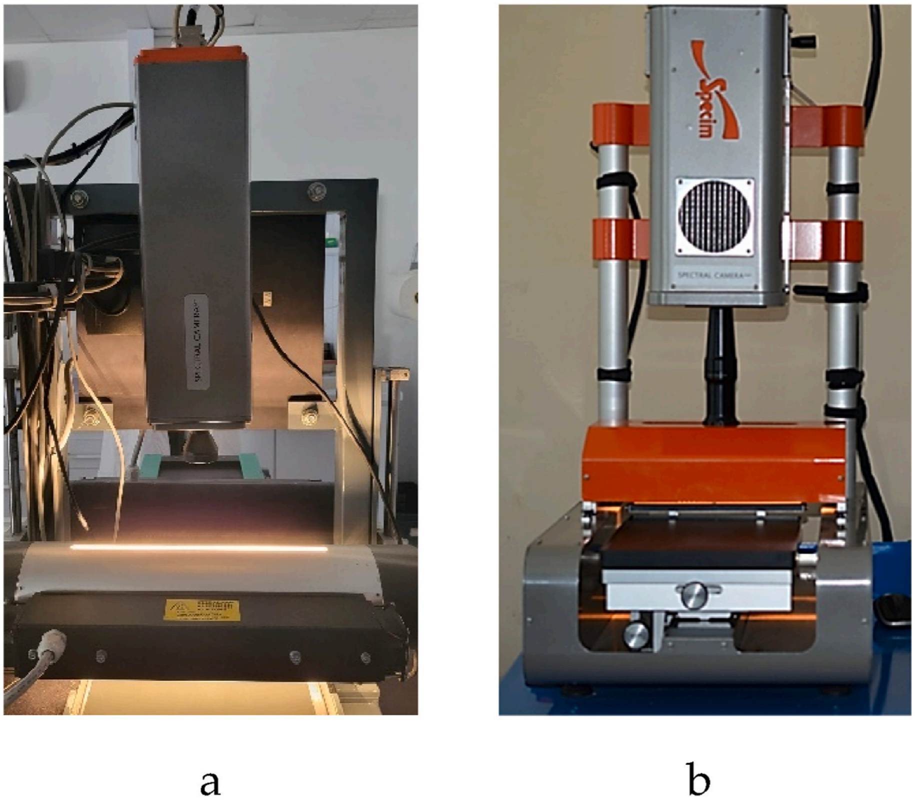


Fig. 2. Overview of the specim ImSpectorTM N17E (specim, Finland) (a) and SISUChema XL™ chemical workstation (specim, Finland) (b).

Keynes, UK) reference was used under the same conditions as the raw image. The following equation was applied to rectify the images:

$$I = \frac{I_0 - B}{W - B} \, x \, 100$$

with I representing the corrected hyperspectral image in a unit of relative reflectance (%), I_0 representing the original hyperspectral image, B representing the black reference image (~0% reflectance), and W representing the white reference image (~99.9% reflectance). This analysis was subsequently conducting using all the rectified images.

3.3. *Spectral data collection, processing, and exploratory analysis*

Hyperspectral images were acquired by scanning the investigated samples line by line, with the resulting data files imported into a PC unit. For the spectral data analysis, the PLS_Toolbox (version 8.8.1, Eigenvector Research, Inc.), equipped with MIA Toolbox and running within Matlab® (version 9.6, The Mathworks, Inc.), was used. Fig. 3 illustrates the applied approach for data analysis.

Initially, the examined wavelengths were reduced to eliminate background noise. Data were then pre-processed to emphasize spectral differences among samples and mitigate the influence of potential external sources of variability. Specifically, standard normal variate (SNV), derivative, and mean center (MC) algorithms were employed for this purpose.

SNV is a widely used pre-processing method for scatter correction (Barnes et al., 1989). The basic formula for SNV correction is as follows:

$$x_{corr} = \frac{x_{org} - a_0}{a_1}$$

where x_{org} represents the original sample spectrum measured by the adopted instrument, x_{corr} is the corrected spectrum, a_0 is the average value of the sample spectrum to be corrected, and a_1 is the standard deviation of the sample spectrum.

Derivatives have been applied in analytical spectroscopy for many years, because they can eliminate both multiplicative and additive influences from the spectra (Rinnan et al., 2009). The present study employed the Savitzky-Golay derivation method, which is a technique for numerical derivation that includes a smoothing step (Savitzky and Golay, 1964).

One of the most commonly used pre-processing techniques is MC, which determines the mean of each column and subsequently subtracts that value from the column. Following mean-centering, each row of the mean-centered data exclusively reflects the variations of that specific row from the average sample in the original data matrix.

In the present study, principal component analysis (PCA) was applied after the above-described pre-treatments as an exploratory method (Wold et al., 1987). PCA is a chemometric technique that compresses data by projecting samples into a low-dimensional subspace with axes pointing in the direction of highest variance (Amigo et al., 2013). The distribution of samples in PC space indicates similar features, as samples with comparable characteristics tend to cluster in the same area. Prior to using a classification model, PCA is a crucial, since it can identify the primary sources of variability. PCE highlights patterns or clusters within samples, providing information on the major substances and their distribution across the measured surface.

Finally, to reach the recognition target, a classification procedure based on partial least squares–discriminant analysis (PLS-DA) was applied (Barker and Rayens, 2003). Classification methods aim at building a model capable of identifying the class to which objects belong, based on a certain number of descriptors. PLS-DA, being a supervised classification method, requires prior knowledge of the data. A discriminant model is developed using samples with known classes, which is then employed to classify new samples composed of the same material as the known ones. PLS-DA is a linear classification strategy that combines the ability to discriminate between classes with the characteristics of partial least squares regression. It builds upon the PLS regression technique, which identifies latent variables exhibiting the highest correlation with Y-variables. Using the spectral signature, the resultant model categorizes each unknown sample in the hyperspectral image into one of the possible classes.

In the present study, following the implementation of the pre-processing techniques outlined in the PCA stage, PLS-DA was employed to achieve effective discrimination among distinct classes and provide predictive information for new hyperspectral images. Fig. 3 shows the adopted schematic procedure, providing a visual representation of the steps taken in the analysis of the HSI data.

4. Results

Collaboration between businesses and universities is essential for promoting clean production and sustainable development by facilitating the exchange of expertise. Building on the previously proposed techniques, this section presents the relevant results of the HSI analysis.

Fig. 4 illustrates the raw and pre-processed reflectance spectra of samples obtained within the NIR, whereas Fig. 5 displays the corresponding spectra acquired in the SWIR. Examining the average raw NIR of the materials under study revealed two distinct spectral regions characterized by notable absorptions, as shown in Fig. 4. The first absorption zone spanned from 1100 to approximately 1200 nm, while the second was observed in the range of 1400–1550 nm. These absorption ranges provided valuable information regarding the molecular characteristics and composition of the materials. The first zone corresponded to the second overtone of C–H stretching vibrations, whereas the second zone was associated with the first overtones of O–H and N–H stretching vibrations, as well as combination bands of C–H.

Within the SWIR, clear absorptions were particularly noticeable in the interval from 1600 to 2200 nm, as depicted in Fig. 5. The dominant features in the 1667–2000 nm region primarily consisted of the first overtone of aliphatic and aromatic C–H stretching vibrations, along with O–H combination bands (Schwanninger et al., 2011). However, assignments in the combination band area (i.e., 2000–2500 nm) were challenging due to the numerous potential combinations of vibrations.

Fig. 6 presents the results of the PCA performed on all the samples used to train the classification model, shown as a PC1–PC2 score plot for both the NIR (Fig. 6a) and SWIR (Fig. 6b). Concerning the NIR acquisitions, PC1 and PC2 accounted for 64.58% and 20.79% of the total variance, respectively. Spectral sample data were grouped into five

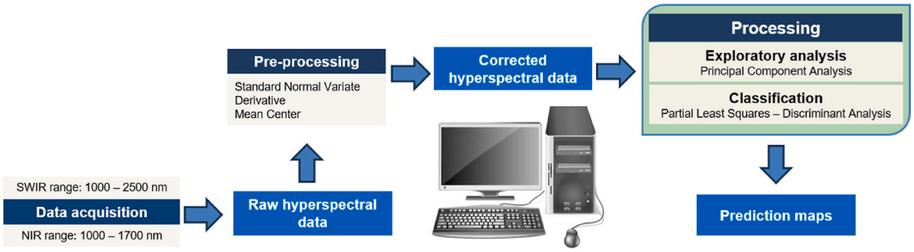


Fig. 3. Flow chart representing the HSI data analysis procedure.

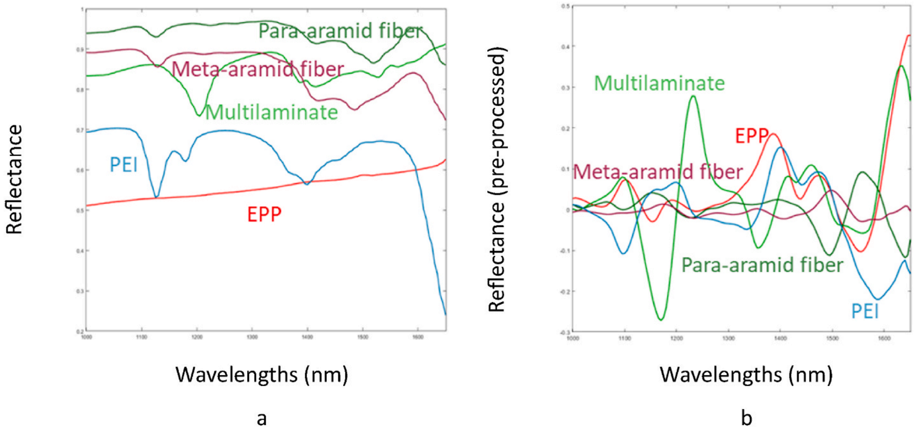


Fig. 4. Acquired raw (a) and pre-processed spectra (b) of the five analyzed materials in the NIR.

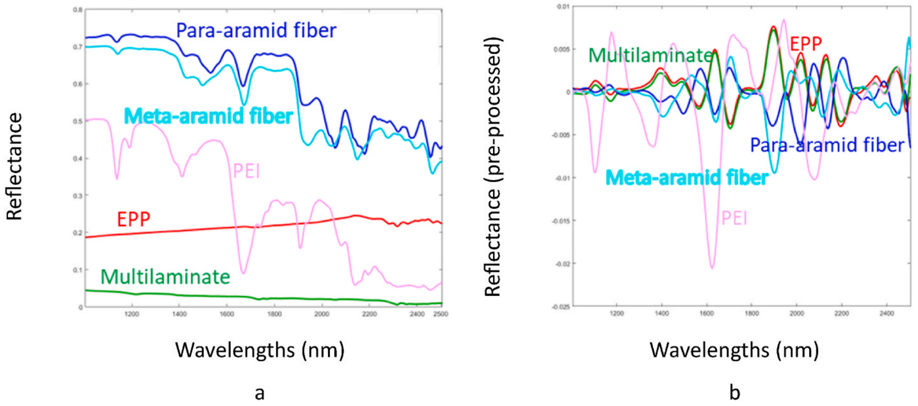


Fig. 5. Acquired raw (a) and pre-processed spectra (b) of the five analyzed materials in the SWIR.

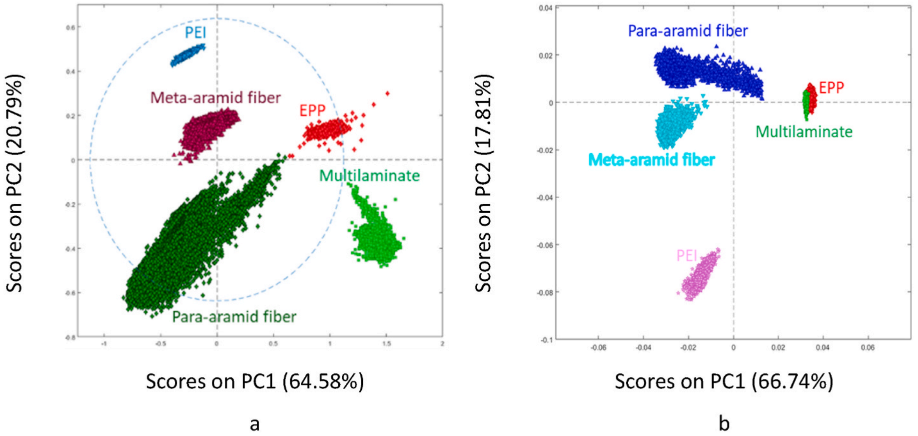


Fig. 6. PCA score plot for the calibration set samples acquired in the NIR (a) and SWIR (b).

categories based on spectral signatures, with no score overlaps observed in the NIR experimental setup. The PCA performed on SWIR spectral data explained a variance of 66.74% with PC1 and 17.81% with PC2, as shown in Fig. 6b. The score plot for PCA applied to SWIR data indicated a slight score overlap between the EPP and multilaminate categories, likely due to the nature of the samples: EPP is very dark, while multilaminate is transparent and thin, making its spectral behavior slightly influenced by the characteristics of the conveyor belt (which, in the present study, was dark).

Figs. 7 and 8 show the results of the PLS-DA model, built using the acquired NIR-HSI data. The outcomes unequivocally demonstrated the efficacy of the proposed PLS-DA model in accurately identifying distinct categories. This success was evident not only in scenarios where samples were well-separated along the conveyor belt (as depicted in Fig. 7), but also when samples overlapped (as illustrated in Fig. 8).

These outcomes were further assessed by considering the *sensitivity* and *specificity* values derived from the NIR classification model, as presented in Table 1. Such values were good across all categories, indicating the robustness of the model. *Sensitivity* and *specificity* are critical metrics used to evaluate classification model performance. *Sensitivity* (i.e., the

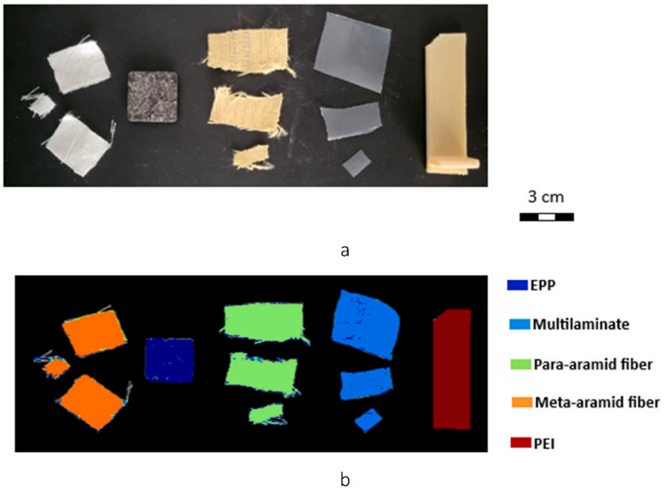


Fig. 7. NIR digital image (a) and predicted image (b) representing non-overlapped particles acquired in the NIR.

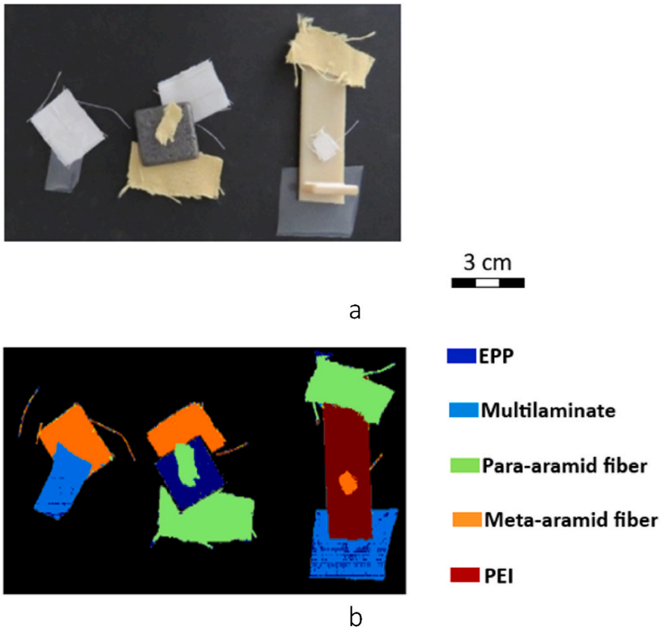


Fig. 8. Digital image (a) and predicted image (b) representing overlapped particles acquired in the NIR.

Table 1
Statistical parameters of the NIR classification model.

	EPP	Multilaminate	Para-aramid fiber	Meta-aramid fiber	PEI
Sensitivity (Cal)	1.000	1.000	1.000	1.000	1.000
Specificity (Cal)	0.997	1.000	0.990	1.000	1.000
Sensitivity (CV)	1.000	1.000	1.000	1.000	1.000
Specificity (CV)	0.997	1.000	0.990	1.000	1.000

true positive rate or recall) measures a model's ability to accurately identify positive cases, with high sensitivity indicating that the model effectively captures most true positives, thereby minimizing false negatives. *Specificity* (i.e., the true negative rate) measures a model's ability to accurately identify negative cases, with high specificity indicating that the model minimizes the incorrect categorization of negatives as positives, thereby preventing false positives. The following equations are used to calculate sensitivity and specificity, respectively:

$$Sensitivity = \frac{TP}{TP + FN}$$

$$Specificity = \frac{TN}{FP + TN}$$

Where TP represents a true positive, FN represents a false negative, TN represents a true negative, and FP represents a false positive.

In summary, *sensitivity* and *specificity* provide valuable insights into model performance characteristics. In the present study, the *sensitivity* and *specificity* of the PLS-DA models, developed using the HSI data, were calculated for both calibration (Cal) and cross-validation (CV).

Figs. 9 and 10 display the prediction images obtained by applying the PLSDA model to the SWIR hyperspectral images. Table 2 shows the *sensitivity* and *specificity* values for both Cal and CV, obtained from the PLS-DA model built in the SWIR. The outcomes of the experimental setup were highly promising. However, it is important to recognize the presence of some misclassifications, particularly with respect to overlapping particles. Specifically, multilaminate layers overlying the meta-aramid particle were sometimes erroneously classified as singular meta-aramid items (Fig. 10).

Of note, the underlap particle was entirely categorized as if no particle was overlaying it, revealing a limitation of the classification model's precision under these specific conditions. Based on these findings, it appears that light depth penetration is more consistently reliable when utilizing the acquisition system in the SWIR, compared to the NIR.

This observation holds significant implications for applications involving material classification, particularly in situations involving overlapping particles. In future applications, the enhanced reliability of depth penetration, particularly in the SWIR, must be considered in various analytical contexts to guide strategic decisions. Moreover, further investigations and refinements of the classification model could address the observed misclassifications and enhance overall system performance. This proactive approach would not only acknowledge the current limitations but also pave the way for continuous improvement, ensuring that the classification system evolves to meet the demands posed by complex scenarios and achieves optimal performance under diverse operational conditions.

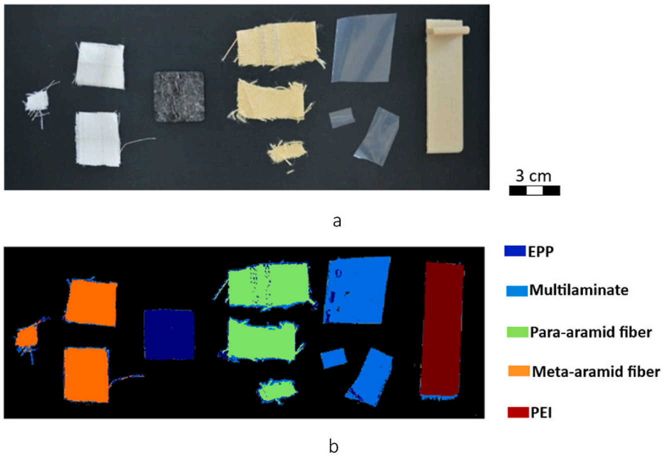


Fig. 9. Digital image (a) and predicted image (b) representing non-overlapped particles acquired in the SWIR.

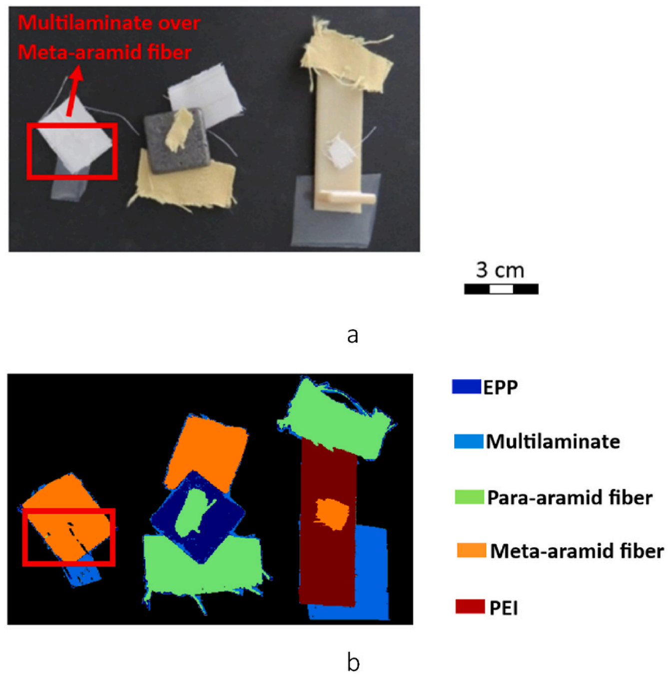


Fig. 10. Digital image (a) and predicted image (b) representing overlapped particles acquired in the SWIR.

Table 2
Statistical parameters of the SWIR classification model.

	EPP	Multilaminate	Para-aramid fiber	Meta-aramid fiber	PEI
Sensitivity (Cal)	1.000	1.000	1.000	1.000	1.000
Specificity (Cal)	0.993	1.000	0.999	1.000	1.000
Sensitivity (CV)	1.000	1.000	1.000	1.000	1.000
Specificity (CV)	0.993	0.999	0.999	1.000	1.000

5. Discussion and future perspectives

The issue of waste management is both controversial and complex. A sustainable approach must align with SDG 12, promoting efficient resource use to optimize production while meeting consumption needs. The circular economy model, which reintroduces resources back into the production cycle, departs from the linear model, which disregards waste value. Reuse, recycling, and recovery are effective components of the circular economy that are capable of addressing various types of material waste (Jabbour Chiappetta et al., 2023; Li et al., 2024). However, in pursuing the circular economy model, it is crucial to avoid rebound effects, whereby consumption habits remain unchanged.

Space sustainability is an emerging theme in the literature (Wilson and Vasile, 2023), and previous research has identified reuse and waste material scenarios to quantify the overall mass of objects in orbit and the economic value associated with such debris (Leonard and Williams, 2023). The findings of these studies suggest that space waste management (Svotina and Cherkasova, 2023) may generate significant opportunities, if properly addressed.

Regardless of the type of waste considered, the waste hierarchy approach indicates that, where possible, materials should be reintroduced into the product life cycle. Optimal waste management therefore requires sustainable alternatives to use of a landfill (Dai et al., 2024; De Oliveira Neto et al., 2018). The present study proposed an approach to identify and classify waste materials without compromising their reuse or recycling potential, in order to determine the most suitable circularity approach.

Advances in technology are crucial for the development of effective methods for removing and recycling space waste. Such methods could be incorporated into future spacecrafts to facilitate easier disposal or recycling of products at the end of their life (e.g., built-in mechanisms for deorbiting or self-destruction). In addition to debris removal, in-orbit servicing missions could also involve the repair, refueling, or upgrading of satellites, thereby extending their operational life and reducing the need for new satellite launches. Moreover, ongoing research and innovation should aim at developing new and improved methods for space waste recycling via advancements in materials science, propulsion systems, and autonomous technologies. Importantly, the management of space waste (i.e., both debris from collisions and waste produced by spacecraft crews) is a complex, global challenge requiring the concerted effort of all international stakeholders.

As technology advances and awareness of space waste increases, more focused initiatives and solutions are expected to emerge. The development of systems capable of recycling materials within spacecraft is an ambitious yet promising goal. Moreover, both the storage and the sorting of homogeneous materials in space for subsequent treatment upon re-entry to Earth, and the establishment of small recycling processes directly on/in spacecraft are beneficial objectives. In the latter scenario, effective space waste management through recognition, classification, and separation is a crucial challenge. The achievement of this objective will not only optimize waste storage, but also facilitate the recycling and reuse of certain recovered materials within the space environment. The exploration of innovative techniques for material identification and recycling (e.g., HSI) adds a new dimension to space sustainability research and clean production, paving the way for more efficient and environmentally friendly space exploration.

Among the limitations of the present study, it should be noted that the analyses referred to space junk around Earth, and not lunar junk. In addition, subsequent environmental, economic, and social impact analyses are needed to quantify the actual sustainable contribution that is likely to result from the reuse/recycling of the identified materials. Regarding the HSI technique, limitations include challenges in the identification of black plastics and the need for predictive models based on the available data. Additionally, misclassification may occur if the training dataset lacks equivalents for the samples to be recognized. To address this, a broader training sample set should be used to enhance the predictive ability of the classification model and assess the effectiveness of the HSI technique across a broader range of samples.

Future research should also investigate the feasibility of applying the HSI technique in microgravity conditions using the adapted light source of spacecraft and/or space stations. However, the direction of research indicates that a complete life cycle analysis from a sustainability perspective (incorporating all three dimensions) will require a preliminary basis of material characterization and a technical approach on which to base subsequent analyses. The HSI approach, combined with a strategy aimed at optimizing resources, offers clear positive spin-offs that extend beyond corporate boundaries.

This study thus identifies pragmatic solutions that underlie climate change, where real problems that cause environmental pollution are addressed with concrete solutions. Waste management presents materials that cannot be re-entered into circulation, but its negative impact must be contained. At the same time, for other materials its recycling or recovery is possible allowing in a comprehensive view and life cycle analysis the opportunity to have sustainable solutions and with raw materials that are available to businesses providing competitive advantages. In an evolving political context, the challenges on space become critical and must be managed by following a sustainable but also cooperative approach among those countries aiming at a real fight against climate change, to foster solutions that support the resilience of cultures and ecosystems.

6. Conclusions

In recent decades, scientists have explored the feasibility of directly collecting and recycling materials in space. This strategic pursuit aligns with the quest for economic advantages and contributes significantly to technological advancements. Recognizing the potential symbiosis between economic benefits and technical progress, the gathering and recycling of materials in space has emerged as a crucial aspect of space exploration and utilization.

To determine the necessary manufacturing equipment (e.g., shredder, extruder) and design effective recycling processes, different types of materials must be identified. However, the design and implementation of analytical techniques to differentiate solid waste types and the products that may be recovered from them through mitigation and recycling is a formidable challenge. The present study focused on the characterization of end-of-life materials associated with space activities, providing relevant insights to guide the development of possible waste recycling pathways. The goal was to develop a rapid, reliable, cost-effective, non-destructive, and non-invasive technique for this purpose. HSI, which facilitates the identification of varied materials based on their distinctive spectral fingerprints, is a recent breakthrough in waste recycling that may contribute to meeting this need.

The present work combined HSI techniques and chemometric methods to classify solid waste types derived from end-of-life materials in space. The adopted procedure offers numerous benefits from a circular economy standpoint, as it is quick, non-destructive, objective, and affordable. The results revealed that the various groups under examination could be effectively identified, recognized, and systematically categorized using the chosen HSI technique. This highlights the utility and efficacy of HSI as a valuable tool for characterizing and classifying diverse waste items in space.

Thus, this preliminary study produced useful results, warranting further research to enhance classification performance, broaden the range of materials to be analyzed, and reduce the number of wavelengths used to increase analytical speed and decrease instrument costs. Moreover, the findings support the primary objective of the work: to establish a foundation for devising targeted and sustainable strategies for the responsible management and potential recycling of space waste generated during missions.

The feasibility of implementing a complete (or partial) recycling process in the space environment is unknown. However, the circularity of resources is essential for the sustainable transition, and space waste, given its increasing volume, should be approached pragmatically and with consideration given to future generations, in alignment with the concept of sustainable space.

CRediT authorship contribution statement

N. Aversano: Writing – review & editing, Writing – original draft, Methodology, Data curation. **G. Bonifazi:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **I. D'Adamo:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **R. Palmieri:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Data curation. **S. Serranti:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **A. Simone:** Writing – review & editing, Writing – original draft, Methodology, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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