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Indoor laboratory experiments for beach litter spectroradiometric analyses

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Marine pollution is a growing global issue, impacting both marine ecosystem and human health. High quantities of debris, mainly composed by plastic items, have been identified both in the coastal area and in the sea environment. Remote sensing techniques represent an useful tool (complementary to the in-situ campaigns) to monitor litter in the coastal environment, especially if the spectral signatures of the debris are known. In this framework, harvested beach litter (plastic items especially) were collected from two sandy beaches. The samples were spectrally characterised by implementing two indoor laboratory experiments with the aim to infer the best wavelengths to be used for beach litter detection via the spectral angle mapper index. Due to lack of a scientific protocol concerning the spectral data acquisition, two experimental setups were carried out to simulate the direct and diffuse illumination conditions. For around 30% of the samples, the spectral signatures are influenced by the two experimental setups. Outcomes suggest that for the majority of the samples green, blue, red-edge and some infrared bands are suitable for the beach litter detection.

Keywords Marine litter, Beach litter, Spectroradiometric analyses, Standardised protocol, Illumination geometry

Marine litter is defined as "any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment"[1]; thus including beach litter as part of wider definition of "marine litter". More than 75% of the litter is abandoned in the touristic areas, during summer season[2]. The escalating dimensions and consequential impacts of marine litter in several fields (marine ecosystem and human activities), demand a united response through the collaboration of scientific committees and government bodies[3]. Scientific community has made important contributions in the definition of the issue, individuating sources, compositions, accumulation areas and activities useful to monitor and contain the marine litter pollutions[4]. The European Commission is working on establish the criteria to evaluate and control the Good Environmental Status (GES) proposed in the framework of the Marine Strategy Framework Directive (2008/56/EC) (MSFD)[5]. Strategies, regulations, and innovative solutions are implemented to mitigate the environmental, economic, and social implications associated with marine litter[6]. Different technologies have been identified to prevent litter from entering in the coastal environment and to monitor the transport of the litter once it ends up into the marine environment. Sampling activities, remote sensing detection and modelling are useful instrument for the marine litter solution[6]. In-situ monitoring campaigns were carried out, over the years, with the main goals to quantify and characterise marine litter in terms of materials and polymeric compositions[7,8]. Unfortunately, these activities are time-consuming especially over large areas. In this framework, an effective alternative is represented by the application of remote sensing techniques employing high spatial resolution acquisitions like those collected by Unmanned Aerial Vehicles (UAV)[9]. With these platforms large and/or inaccessible areas (such dunes, rivers and lakes) could be monitored employing a reduced human effort as highlighted by Andriolo et al.[10]. The main limitations of beach litter detection via proximal remote sensing over sandy background was investigated in Guffogg et al.[11] and the useful wavelengths for the detection were individuated[12]. Although aerial images allowed to quantify marine litter debris, in some research work such as in Escobar-Sánchez et al.[13] is underlined that only the items characterised by a size more than ten times than the spatial resolution (i.e. items of > 2.5 cm) were detectable; however, these items are not identifiable due to their extensive variety in shapes, sizes, colours and materials.

A possible chance to overcome these limitations is increasing the knowledge of marine litter spectral signatures aiming to train more adequate supervised classification algorithms[14,15]. The spectral signatures of dry virgin polymers are well-established and widely employed in the material recovery sector for recognizing

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plastic items by the others waste[16] and discerning polymer types[17]. Currently, there is a lack of spectral data of real marine plastic debris in different conditions since these materials are subjected to weathering actions due to winds and currents (mechanical degradation) and chemical/physical degradation. This scientific gap is being gradually filled by the scientific community involved in the spectral characterisation of the marine harvested debris through both indoor and/or outdoor experiments. Spectral libraries were realized in De Vries et al.[18] in which both virgin polymers and biofueled plastics were spectrally characterised employing an hyperspectral camera (indoor and outdoor experiments). Analyses of dry plastic items were conducted in a dark laboratory and compared with the dataset acquired in wet and submerged conditions[15]. Additionally, Garaba and Dierssen[19] performed outdoor acquisitions employing the PANalytical Boulder ASD FieldSpec 4 spectroradiometer to infer spectral similarities of micro- and macro- marine harvested litter with virgin polymers (in the range from 350 to 2500 nm). Some experimental setups are not in deep described (e.g. Acuña-Ruz et al.[20]), thus not allowing the replicability of the measurements. Other experimental setups are well described but are related to the use of thermal infrared spectral measurements on marine harvested debris (e.g. Garaba et al.[21]). Based on the spectral data ad-hoc acquired on virgin and marine harvested plastic items, the main limitations for marine litter detection via remote sensing techniques were evaluated[22].

Moreover, several methodologies are applied to process the collected spectra[23] including the use of spectral contrast angle[24], the employment of the spectral angle mapper (SAM) or of the vector distance (Euclidean distance measure, ED).

The absence of a standardized protocol concerning both the spectra data acquisitions and their analyses is causing a not-homogeneity of the spectral dataset available in the literature. Considering the high variety of the polymers in terms of shape, dimension, chemical composition etc. it is evident the need to infer the influence of the illumination conditions in the spectral signatures data. In this framework, the main objective of this research is to realise spectral libraries of harvested beach litter, using two different laboratory setups characterised[25] by direct and diffuse illuminations conditions. The comparison was performed in terms of SAM index, which could be applied also to hyperspectral images. The two spectral libraries allowed to compute SAM among each sample and sand with the aim to test the influence of the illumination conditions in the selection of the more promising spectral bands to be employed for an outdoor detection. Indeed, the outcomes of the described laboratory experiments could in the future drive beach litter satellite sensing which is in a rapid development in recent years (improvements of number of bands and spatial resolutions are expected) and UAV outdoor applications employing expensive light hyperspectral sensors (such as RIKOLA, HySpex, Senop, Cubert cameras).

Results

Analysis of the spectra and role played by the illumination geometry

Spectra of the sand and of some of the samples are reported in Fig. 1.

Most of the spectra acquired within the white box (diffuse illumination setup) are characterised by absorbance peaks in typical wavelengths[26] such as 930, 1200, 1400, and 1700 nm.

Similar results were achieved using the black box (direct illumination setup).

Noticeably that, the spectral signature of sand is monotonically increasing in the 350–1350 nm range, the spectral signature is than characterized by a plateau, with the exception of the well-known absorption peaks observable only indoor (around 1400 and 1900 nm) due to its water content. As expected, the spectral signatures of the collected samples exhibit reflectance peaks in the visible range of the spectrum, consistent with their colours. However, peculiar absorption peaks are observed in the NIR (around 950 nm) and SWIR (1200, 1350, 1720 nm) regions. Noticeably that, for the samples reported here (which are made of plastic), the absorption peaks due to water content (which is absent) are not evident.

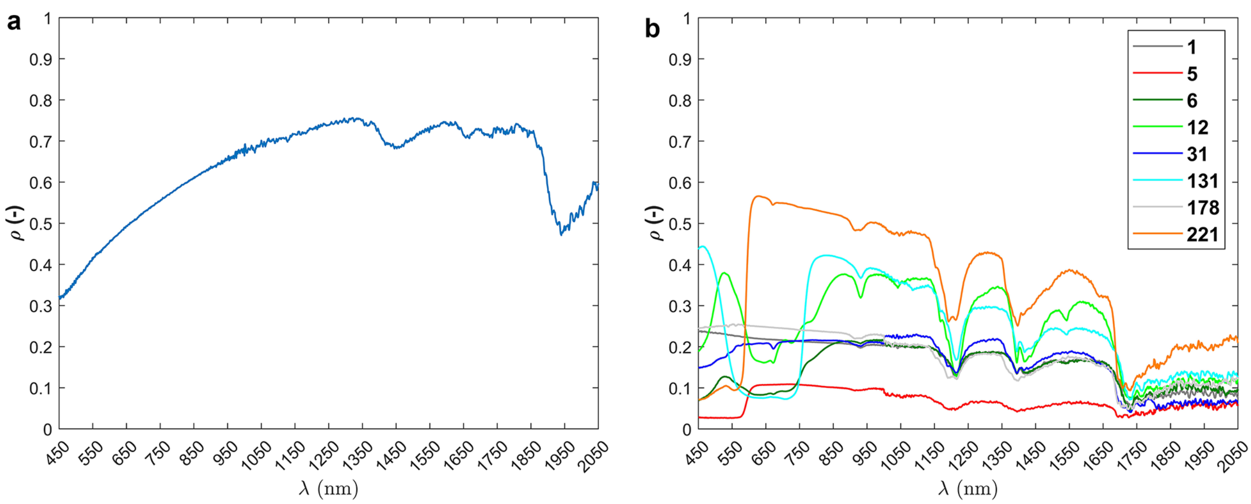

Fig. 1. Spectral signatures of sand (**a**) and of some harvested beach litter (**b**), reported in Fig. 7, acquired within the white box.

The average of the whole spectra (450–2100 nm) acquired within the white $\rho\mu_{s,\,white}$ and the black $\rho\mu_{s,\,black}$ box (Fig. 2) highlighted that for some of the spectra, the illumination condition played an important role as shown by the low R^2 of the $\rho\mu_{s,\,white}$ vs. $\rho\mu_{s,\,black}$ relation (~ 0.43). Around 70% of the data fall in the buffer area (green band, Fig. 2) of ± 0.1 (10% of the reflectance) from the 1:1 line meaning that for these samples the illumination conditions did not influenced the measurements (R^2 ~ 0.92, computed among the black dots in Fig. 2). Instead, for ~ 30% of the whole data, the illumination setup influenced the reflectance data (for same samples this was higher if acquired in the white box, blue dots, and vice versa, orange dots; Fig. 2).

Beach litter detectability on a sandy background – use of SAM index and comparison between the illumination geometry

The effect of the different illumination conditions was evaluated by determining the SAM among the spectra of the debris vs. sand, hereinafter referred as "debris – sand pair". Slightly differences are noticeably between SAM values achieved by employing diffuse and direct illumination (Fig. 3, panel *a* and *b* respectively). SAM lower than 0.2 (i.e. of samples scarcely detectable from the sand) are achieved by 18% and 15% of the total samples acquired inside the white and black box respectively. Instead, the 21% and 37% of the samples (for the white and the black setup respectively) are characterised by SAM values ~ > 0.5 and thus are moderately-highly distinguishable from sand. Noticeably, SAM values are in general slightly higher for the signatures acquired inside the black box (Fig. 3, panel *c*) with around 20% of samples characterised by points far from the 1:1 line.

Individuation of the best spectral bands suitable for beach litter detection on sandy beaches and best currently operating sensors

By employing a moving window of 21 nm (i.e. considering reflectance within a 21 nm wide range which scroll in the whole spectra) the SAM of each sand-sample pair was evaluated. Slightly differences between the white and the black setups (Fig. 4, panels a and b respectively) were observed. For some samples peculiar bands (often located in the visible part of the electromagnetic spectrum) are to be employed for their detections; vice versa, for the majority of the samples the more suitable bands are positioned: (i) in the visible (450–630 nm) range; (ii) around the red-edge wavelength (700–770 nm); (iii) approximately at 1230 nm, 1400 nm and 1720 nm. Noticeably that bands located between 800 and 1000 nm, 1250–1300 nm and around 1450–1650 nm are not useful for the litter debris detection (i.e. characterised by SAM ~ < 0.2).

Discussion

The most common approach to quantify and characterise the beach litter are the in situ monitoring campaigns, regulated by standardized protocols[27]. Several limitations characterise this approach such as the high number of operators required, the significant time investment they demand and, finally, the difficulties to sample large areas in a reasonable time. Some of these limits, such as the numbers of operators involved or the possibility to monitor larger area, can be overcome through the implementation of several remote sensing techniques, recently proposed (e.g., Gonçalves et al.[25]) like the UAV to detect beach litter (e.g., Scarrica et al.[28]). These tools allow to infer on the abundance and the spatial distribution of beach litter[13]; however, it is not possible to identify the and characterise the plastic debris due their heterogeneity in terms of shapes and colors and due the lack of information regarding their spectral signatures[29,30].

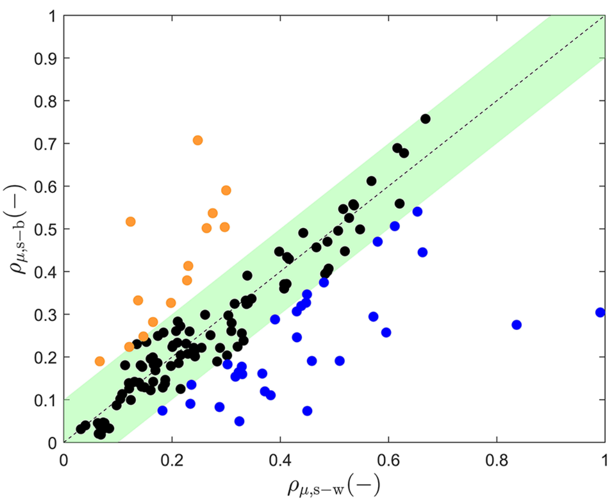

Fig. 2. Average of the i-th sample spectral signature acquired within the white box ($\rho_{\mu,s-w}$ in x-axis) vs. the one acquired in the black box ($\rho_{\mu,s-b}$ in y-axis). The green band encloses the samples only slightly influenced by the illumination conditions (inside the ± 0.1 reflectance from the 1:1 line). Blue dots refer to the samples characterised by a higher average reflectance in the white box; orange dots, refer to the samples characterised by a higher average reflectance in the black box.

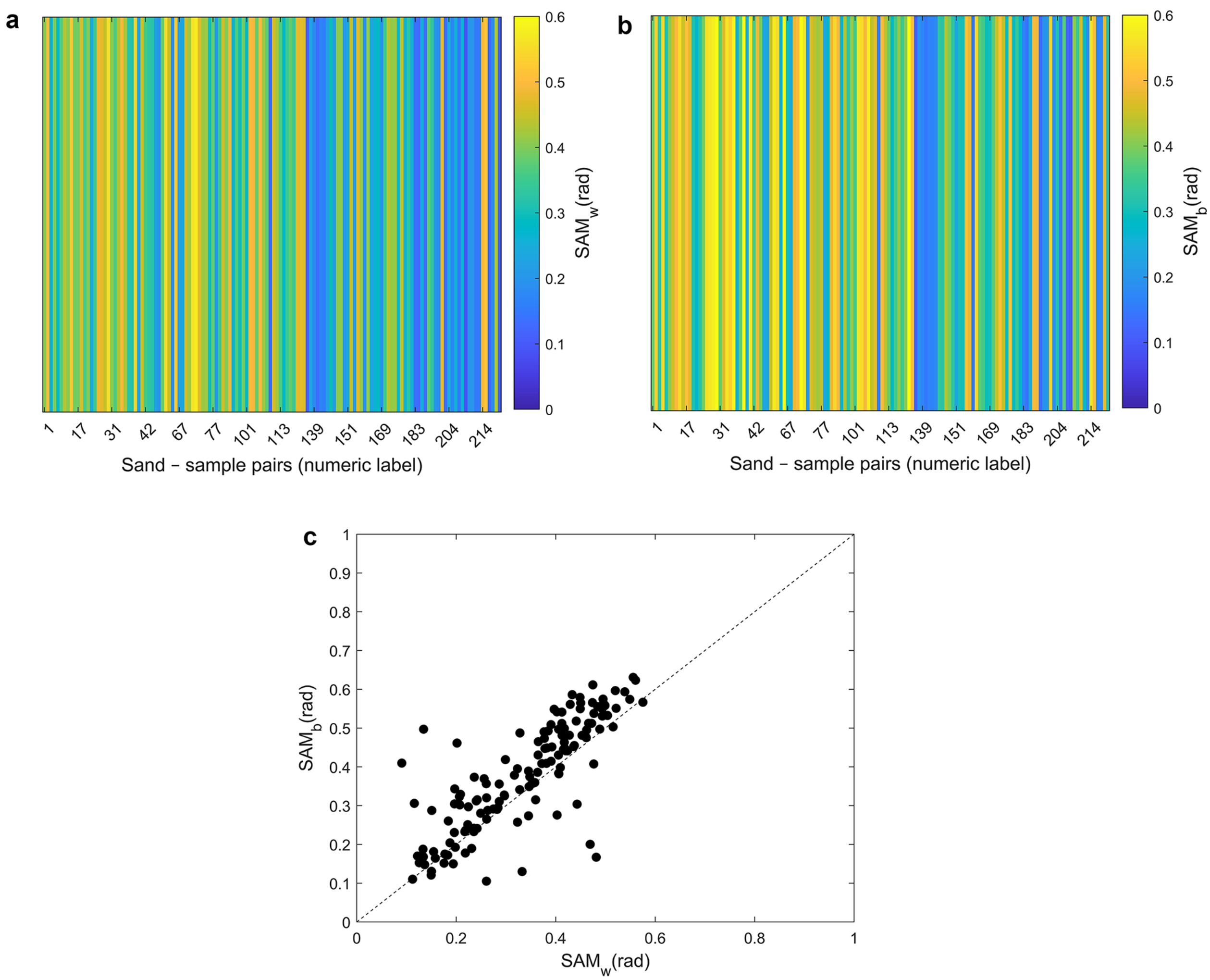

Fig. 3. SAM index values evaluated for each sand-sample pairs acquired within the white, SAM_w (**a**) and the black, SAM_b (**b**) box respectively. SAM values comparison between the two experimental setups (white box, SAM_w, in x-axis and the black box, SAM_b, in y-axis) (**c**).

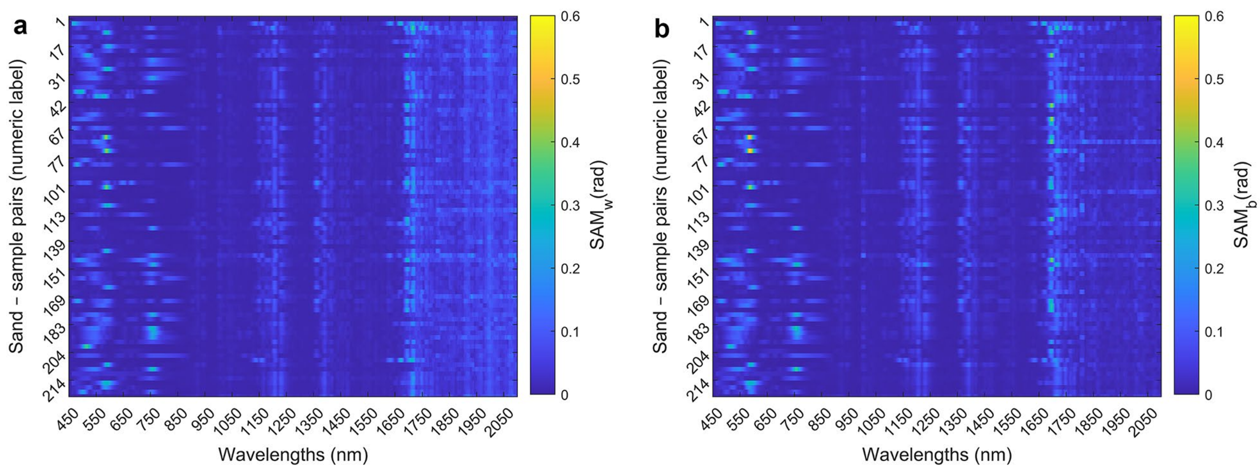

Fig. 4. SAM index (sand - sample pairs) evaluated considering a moving window of 21 nm. Data acquired inside the white (**a**) and the black box (**b**).

In this context, marine debris have been spectrally characterised in different research activities, contributing to increase the online spectra library[26,31]. The non-homogeneity with which these data have been acquired, did not allow the replicability of the experiments, and cause a heterogeneity on the spectra.

This research activity was focused on the comparison between the data acquired on harvested beach litter carrying out two different experimental setups mainly differentiated in the illumination conditions: (i) direct light inside a black box and, (ii) diffuse light in a white box. The comparison between the spectral data acquired within the two boxes, highlights that for most of the samples, the illumination geometry did not affect the spectral signatures, whereas it is crucial for ~ 30% of the total samples, characterised by peculiar shapes and/or with a very smooth surface (not Lambertian). The laboratory experiment allowed also to detect some common absorption peaks in the following ranges: 900–950 nm, 1160–1300 nm, 1380–1430 nm, 1520–1560 nm and 1715–1750 nm. These results are in agreement with outcomes of other studies (e.g., Garaba and Dierssen[19]).

The comparison between the SAM index (samples vs. sand) for both boxes, highlights that for some samples, the illumination geometry played an important role.

The most suitable wavelengths for the beach litter detection have been selected using, over the SAM index, a moving wavelength window of ~ 21 nm. For several samples, the most useful bands are positioned in the visible, red-edge and in some infrared bands (~ 1230, ~ 1400 and ~ 1720 nm). Similar results are reported in Salgado-Hernanz et al.[32] and in Guffogg et al.[12], in which indoor and outdoor analyses have been conducted. Nevertheless, bands around 1400 nm cannot be operatively used for an outdoor detection because affected by atmosphere water vapor absorption in thus band.

This work represents one of the first comparison between spectral signatures collected employing direct and diffuse illumination conditions filling a gap in the spectroradiometric characterisation of beach litter. Thus providing useful information for the definition of a standardize protocol. Future developments of this activity will concern the identification of the currently operating satellite sensors more promising to detect litter on sandy beaches. Additionally, the polymeric composition of the samples will be investigated jointly with a Fourier Transform Infrared Spectroscopy (FTIR) analysis. Finally, the detectability of the samples in outdoor condition will be assess by employing an UAV equipped with an hyperspectral camera.

Material

Beach litter and sand samples have been harvested from two Sicilian sandy beaches, Mondello and Isola delle Femmine, reported in Fig. 5.

The items collection has been conceived and performed considering the "Guidelines for the monitoring and assessment of plastic litter in the ocean" (GESAMP 2019) protocol. The activities have been supported by the Interreg Italy Malta territorial cooperation project SenHAR "Campagne di sensibilizzazione per una armonizzazione Italo-Maltese per un buono stato dell'ambiente" C.2-3.1-115.

The samples collected were spectrally characterised in laboratory by means of two experimental setups differentiating for the illumination conditions. The heterogeneity of debris in beach's environment, causes high variability in terms of colour, dimensions and shape of the litter collected. Several objects were identified such as bottle, cups, children's toys etc. and, additionally, several items were fragmented making difficult to determine from which object derived. Totally 221 items were categorized and numbered. Excluding the transparent ones, a total of 136 samples were spectrally characterised (some of them are shown in Fig. 6). The pictures of all samples are reported in the supplementary material section. The plastic items within the samples collected were all macroplastics (> 5 cm).

The instruments used in both experiments are the spectroradiometer, the personal computer and the lamps, schematized and reported in Fig. 7.

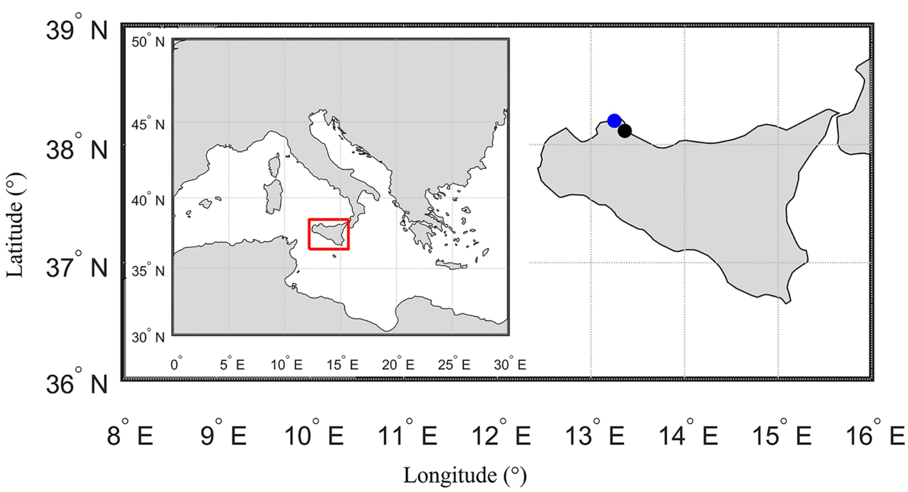

Fig. 5. Beaches harvested during the in-situ monitoring campaigns. Black and blue dots represent respectively Mondello and Isola delle Femmine beaches. This map was produced using MATLAB® *version 9.13.0 (R2022b)*. Natick, Massachusetts: The MathWorks Inc.; 2022. https://www.mathworks.com.

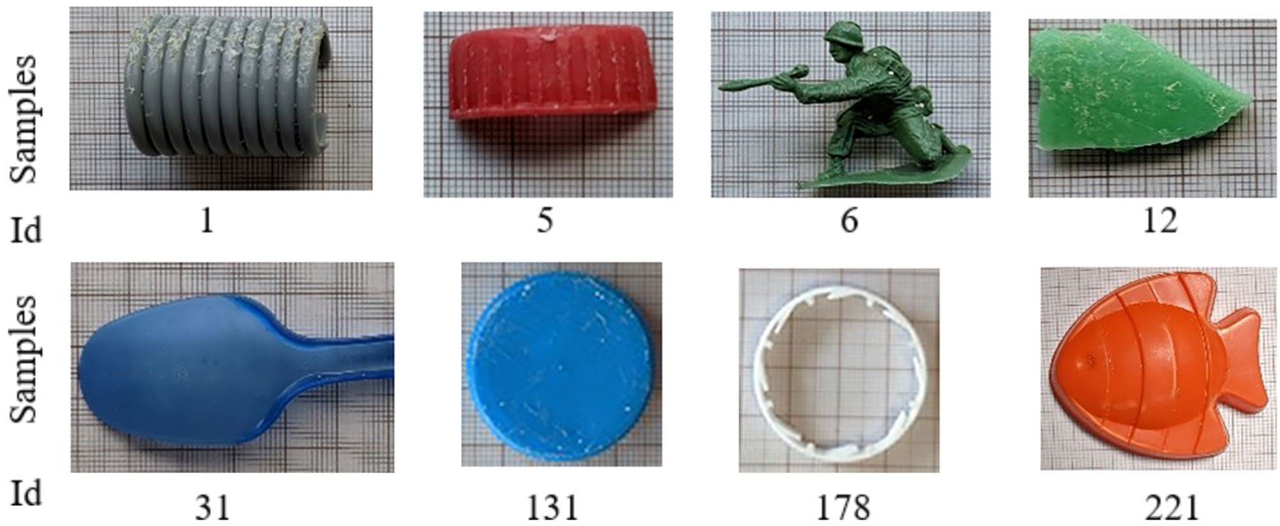

Fig. 6. Pictures of eight samples collected during the monitoring campaign (their spectral signatures were reported in Fig. 1).

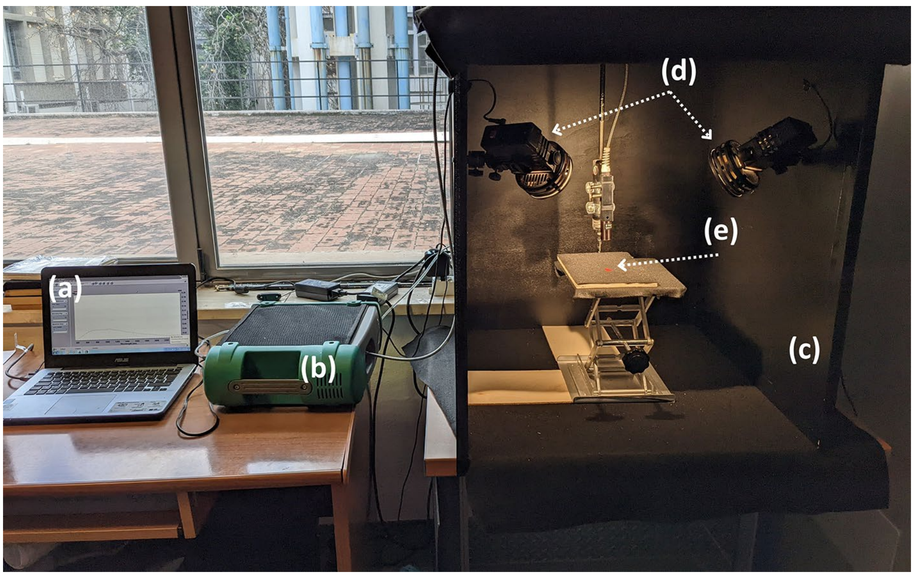

Fig. 7. Experimental setup: personal computer (**a**), spectroradiometer (**b**), box (white and black) (**c**), lamps (**d**), sample (**e**).

The spectroradiometer used to acquire the spectral data is the FieldSpec 4 Hi-Res spectroradiometer by ASD (Analytical Spectral Devices). It acquires spectral signatures across the entire solar-reflected spectrum (i.e. from 300 to 2500 nm) by means a 1.5 m long optical fiber with a field of view of 25°. The three spectrometers composing the instrument are operating in the visible VNIR range (350–1000 nm; spectral resolution of 3 nm), in the infrared ranges named shortwave 1 (1001–1800 nm; spectral resolution of 8 nm), and shortwave 2 (1801–2500 nm; spectral resolution of 8 nm). The instrument was connected to a personal computer used to store the data and set the spectroradiometer.

In both experiments the samples were illuminated using two ASD pro-Illuminator Reflectance Lamp Halogen equipped with Single-Ended Quartz JC14.5 V-50WC lamps characterised by an irradiance curve which approximate that of the sun.

The two boxes were ad-hoc realized considering the dimensions of the samples and properly place the lamps to create the different illumination conditions. Both the painting and the shape of the boxes were chosen in order to facilitate the realization of direct and diffuse lighting conditions. The former was facilitated using a black paint and building the top of the box horizontally; instead, the second applying a white paint and building the top of the box with a 'cupola' shape. For each purpose, different paints have been selected and spectrally characterised (through the spectroradiometer) on a small wood sample: the paints selected were the ones with the highest reflection and absorption properties, respectively. The volumes of the boxes were quite similar ($60 \times 70 \times 60\,cm$ and $60 \times 60 \times 60\,cm$ for the white and black boxes respectively).

To ensure the accurate acquisition of the spectral signature of small-sized samples, an optics of 8° was used and a tripod was used to place the samples for the measurements. To avoid background influences, the samples have been positioned above a black (21 × 15 × 1 cm) panel, realized covering a wood board with a black opaque fabric. The incident irradiance was acquired by using a barium sulphate panel (21 × 20 × 1 cm), reflecting the 100% of the flux incident.

Two curtains, previously spectral characterised and matched with the colors of the box, were positioned to avoid the influences of external lights and of the operator.

Methods

Experimental setups

A total of 136 harvested beach litter were spectrally characterised within two boxes where the two illumination conditions were realized. Within the black box, quasi-totally adsorbing the light, the direct illumination of the i-th sample was ensured by positioning the sample centrally and in line with the lamps; these latter were rotated and tilted to illuminate the sample at 45° from two directions. In the white box, quasi-totally reflecting the light inside, the diffuse illumination was realised rotated and tilted the lamps to illuminate the cupola-shaped top of the box at 45° from two directions; the sample was placed in the centre of the box. Pictures of the experimental setups are reported in Fig. 8.

Spectral signatures collection

The instrument used to spectral characterise the sand and the harvested samples was the spectroradiometer. The instrument allows to directly collect the in-reflectance data. Nevertheless, it was preferred to acquire the data in-radiance (computed as the average of 20 repetitions) and to calculate the reflectance of the i-th object as the ratio between the radiance of the object and of the barium sulphate panel: the latter corrected with the calibration curve of the white panel. This methodology allows to verify that the illumination conditions remained constant (or not) throughout each sampling cycle (the whole spectral laboratory experiment was carried out in different measurement sessions/cycles per day, approximately for 20 days). Before each measurement cycle the instrument was optimize, allowing to measure and correct the instrument noise, by performing the "dark current" procedure. Moreover, according to the spectroradiometer handbook, before each measurement session the instrument was turned on at least 30' to ensure the stabilization of its temperature which is ensured by an internal cooling system thus, ensuring the minimization of the internal noise during the measurements.

The spectral acquisition of the sand and of the samples was realized maintaining constant (equal to 6 cm) the distance between the 8° optical and the sample (moving opportunely the tripod in which the samples were positioned). Indeed, in Corbari et al. 2020 was highlighted the importance of this distance, that can highly influence the indoor measurements because of the proximity between the samples and the light source. For the samples smaller than the measurement footprint (diameter ~ 0.85 cm) a series of pieces were placed next to each other to ensure the acquisition of the pure spectral signature of the samples. The comparison between the data

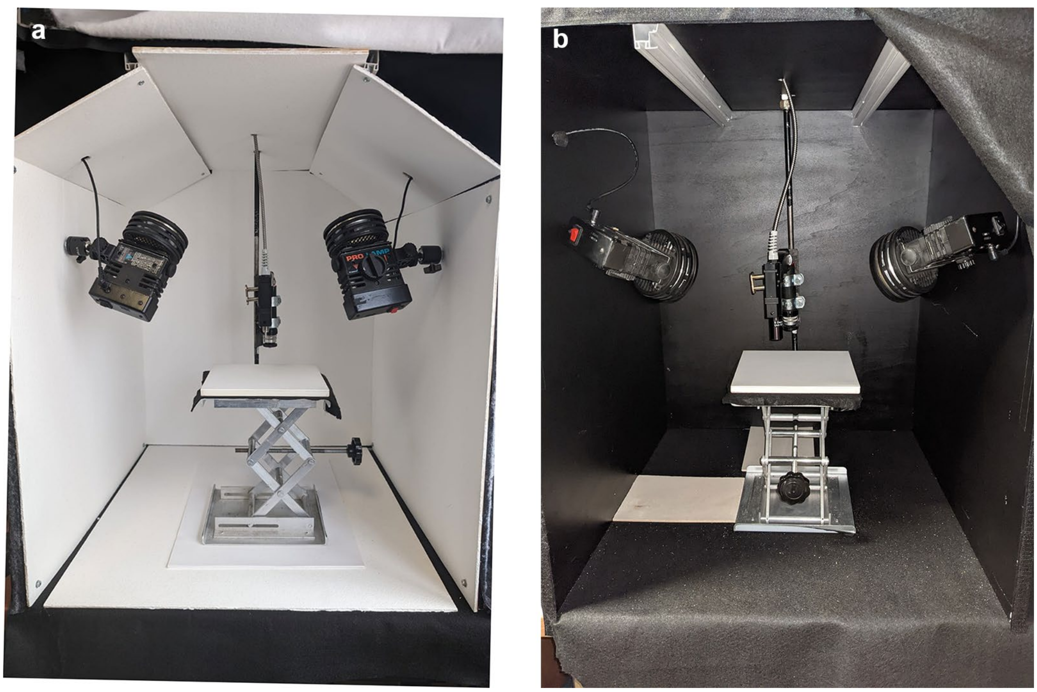

Fig. 8. Pictures of the experimental setups: white (**a**) and black (**b**) boxes.

acquired was ensured following the same methodology for all samples. By taking into account the high noise of measures below ~450 nm and above ~2100 nm, the data analyses were carried out excluding these ranges.

Analysis of the spectra and role played by the illumination geometry
The comparison between the measures conducted within the black and white box was done by averaging the spectral signatures on the whole wavelength range for each sample, *s*.

The average values, indicating as $\rho\mu_{s,\ black}$ and $\rho\mu_{s,\ white}$ respectively for the black and white boxes, were compared in a scatterplot. The samples corresponding to the data not aligned in the 1:1 line were furtherly investigated as they are strongly affected by the two different illumination conditions.

The use of the SAM index as a tool for detectability of the beach litter from sand and influence of the illumination conditions
The possibility to detect the beach harvested debris from sand was evaluated by calculating the spectral similarity/dissimilarity index, named Spectral Angle Mapper (SAM), considering both the spectra acquired in the black and in the white box.

The SAM index, α, is computed as follows:

$$\alpha = cos^{-1}\left(\frac{\sum_{i=1}^{n} t_i r_i}{\sqrt{\sum_{i=1}^{n} t_i^2}\sqrt{\sum_{i=1}^{n} r_i^2}}\right) \quad (1)$$

in which *n* is the number of the spectral bands, t_i and r_i are the two spectra to be compared[33,34].

This index measures the spectral angle between two signatures, evaluated in radians (thus it ranges between 0 and π/2). Small angle between the signatures (low SAM values) means that two objects are similar and, consequently, it is difficult to distinguish each other and vice versa.

In this research work, the SAM index was calculated comparing the spectral signature of the collected litters and that of the sand, both considering the whole wavelength and by employing a moving window. The former allowed to evaluate how many (and which) samples are distinguishable from sand; instead, the latter to individuate the best spectral bands suitable for litter detection on sandy beaches.

The role played by the illumination geometry was investigated comparing, in a scatterplot, the evaluation of the SAM index using data collected both within the black and white box.

Data availability
All data generated during this study are available from the corresponding authors upon request.

Received: 10 May 2024; Accepted: 24 September 2024
Published online: 21 October 2024

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Acknowledgements
Marine debris and sand samples have been harvested from two Sicilian sandy beaches, the data collection has been conceived and supported by scientist at the Laboratory of Ecology, of the Dipartimento di Scienza della Terra e del Mare (University of Palermo) by applying EU standardize protocols. The activities have been supported by the Interreg Italy Malta territorial cooperation project SenHAR "Campagne di sensibilizzazione per una armonizzazione Italo-Maltese per un buono stato dell'ambiente" C.2-3.1-115.

Author contributions
L.C., M.C., F.C. and G.C. conceived and planned the experiments. L.C. made the laboratory acquisition and drafted the first versions of the MS. F.C. and G.C. coordinated the experiment. M.C. and G.C. provided instrumentations. L.C. has the role of corresponding author. All authors contributed to the final version of the MS.

Declarations

Competing interests
The authors declare no competing interests.

Additional information
Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-024-74278-8.

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