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ECOSYSTEM POLLUTION AND EFFECTIVE NATURAL RESOURCES MANAGEMENT

Plastic pellet pollution in the Aeolian Islands UNESCO site (Italy, Western Mediterranean Sea): results of a comprehensive characterization and monitoring study

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Abstract

The archipelago of the Aeolian Islands in the Tyrrhenian Sea is a globally important natural laboratory. The archipelago, declared a UNESCO World Heritage Site for its unique geology and biodiversity, offers a unique opportunity to study plastic pollution. This study presents an initiative to assess the occurrence of plastic pellets on the beaches of five Aeolian Islands. It provides an insight into the polymer composition and the effects of degradation. Collected pellets were analyzed using stereomicroscopy and Fourier transform infrared spectroscopy (FTIR). Hierarchical cluster analysis (HCA) based on the results of the FTIR data has proved to be an effective statistical method in identifying different clusters corresponding to different degradation phases of the collected pellets. The infrared analysis identified polyethylene (80%) as the main polymer, with a small amount of polypropylene (20%). It was found that the surfaces of some pellets undergo changes during weathering that alter the polymer surfaces. By combining data on plastic pellets from the Aeolian Islands and surrounding coastal areas, we are gaining a more comprehensive understanding of the distribution patterns of microplastics. The results of the monitoring and characterization are expected to support the developing of waste management and remediation strategies for this environmentally sensitive region.

Keywords Aeolian Islands · UNESCO-World-Heritage Site · Plastic pellets · FTIR analyses · Tyrrhenian Sea

Introduction

The accumulation and dispersal of pre-production plastic pellets, commonly known as nurdles, has been extensively documented worldwide (e.g., Thompson 2006, 2015; Balasubramanian et al. 2010; Hidalgo-Ruz et al. 2012; Reisser et al. 2013; Sharma et al. 2021). Losses during the transportation and processing of raw materials for plastic production have resulted in extensive pollution of oceans, seas, and coastal areas by plastic pellets (GESAMP 2016; Llorca et al. 2020). Plastic pellets are only a few millimeters in size (1 to 5 mm) and, once released, are easily transported by ocean currents (Turner and Holmes 2015). Due to their small size, they, like other types of plastic debris, can be easily ingested by marine life, which can result in plastic entering food webs and impacting ecosystem health (Fendall and Sewell 2009; Tanaka et al. 2013; Setälä et al. 2014; Deudero and Alomar 2015). As for other types of plastic debris, there is plenty of information on the distribution of plastic pellets (e.g., Carpenter and Smith 1972; Gregory 1977; Zbyszewski et al 2014; Fernandino et al. 2015; Karlsson et al. 2018; Corcoran et al. 2020; Operation Sweep the Creek; The Great Nurdle Hunt). However, our understanding of the main sources and pathways through which plastic pellets enters the oceans and seas is extremely limited (National Oceanography Center Report 2021), and long-term monitoring data are needed to understand their dispersion patterns and sources.

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The Mediterranean Sea is considered a hotspot for microplastic pollution due to its semi-enclosed nature, large coastal communities, and industrial activities along the coasts (UNEP/MAP 2016). Many studies have documented the widespread occurrence of plastic pellets on Mediterranean beaches (Laglbauer et al. 2014; De Lucia et al. 2014; Cózar et al. 2015; Faure et al. 2015; Donato et al. 2024). Satellite models indicate that this is a zone where plastic accumulates, originating from the surrounding watersheds and the Atlantic Ocean (Martí et al. 2020). Sources of plastic pellet contamination include spills during manufacturing, improperly secured cargo, and inland runoff that carries pellets into coastal waters (O'Brine and Thompson 2015; GESAMP 2016). Once the pellets are in the sea, they spread via ocean currents and wash up on the coasts (Reisser et al. 2013; Karlsson et al. 2018). Recent research has shown that the presence of plastic pellets in the sediments of the Mediterranean Sea is qualitatively consistent with nearby industrial polymer production (Suaria et al. 2016; Frias et al. 2018; Donato et al. 2024). Accordingly, this study investigated pellet contamination on the Aeolian beaches to provide information supporting protection effort under the European Union's Marine Strategy Framework Directive (MSFD 2008/56/EC).

Italy, with over 8,000 km of coastline around the Mediterranean and its main islands, is a major entry point for plastic pellet pollution (Istat 2015). As an industrialized country with petrochemical production facilities close to population centers, Italy represents a potential major source of plastic pollution to the surrounding marine ecosystems (UNEP/MAP 2016). Previous studies have documented the ubiquitous presence of plastic pellets on beaches from the northern Adriatic to Sicily, with concentrations of up to 1200 pellets/m^2 reported (Schmid et al. 2021; Cozzarini et al. 2023; De Falco et al. 2019; Gomiero et al. 2021; Donato et al. 2024). The identification of polymers has linked the found plastic pellets to probable pollution from Italian processing plants (Karlsson et al. 2018; Gomiero et al. 2021). The dynamics of coastal transport cause the litter to concentrate along the coasts by the longshore drift cells created along the Italian peninsula, while population centers and industrial areas continuously contribute to the pellets entering the sea via stormwater runoff and sewage (Caruso et al. 2022).

Microplastics pose a direct threat to the ingestion of marine organisms as they are similar in size to common prey. Once in the gastrointestinal tract, microplastics can cause intestinal blockages, inhibit growth, and impair food intake (Wright et al. 2013; Au et al. 2015; Fossi et al. 2018; Consoli et al. 2019). A large number of Mediterranean taxa, including many commercially important species, have been found to ingest plastic pellets (Bour et al. 2018; Pellini et al. 2018; Bergami et al. 2019; Solomando et al. 2022). In addition, they can disturb fragile ecosystems and impair valuable services such as carbon sequestration and coastal protection. However, more targeted data on the amount of pellets, dispersal pathways, and long-term trends in the Mediterranean are needed to develop mitigation strategies.

The overall aim of our study is to contribute to the deepening of knowledge on plastic pellet pollution in coastal areas and in particular on the beaches of the important Aeolian archipelago in the Tyrrhenian Sea. In detail, our objectives are the following: (1) to provide an initial basis for ongoing monitoring actions by characterizing microplastic pollution on five major islands through stereomicroscopy and Fourier transform infrared spectroscopy (FTIR); (2) to propose a statistical method to assess the degradation of pellets using Hierarchical Cluster Analysis (HCA); and (3) to draw attention to the presence of microplastics in environments normally considered pristine, while motivating actions to protect their integrity.

The Aeolian volcanic islands, known as the "seven pearls of the Mediterranean," form a unique landscape that has been declared a UNESCO World Heritage Site for its exceptional geology and biodiversity (PDG-UNESCO 2013). Due to their location in the Mediterranean Sea and their dependence on marine ecosystems, these islands are highly vulnerable to microplastic pollution from the surrounding waters. Providing facts and recommendations can raise awareness of this problem and encourage sustainable practices, thereby protecting this invaluable UNESCO site. Our research directly supports the objectives of the EU Marine Strategy Framework Directive (MSFD 2008/56/EC) on the assessment and management of pollution in coastal ecosystems. The MSFD specifically targets plastic pellet pollution and emphasizes the need for member states to assess the impact of pollutants on the marine environment. MSFD Descriptor 10 "Marine Litter" and the corresponding criterion *D10C1* highlight the importance of ensuring that the composition, quantity, and spatial distribution of litter on the coast, in the surface water layer, and on the seabed are at levels that do not harm the coastal and marine environment. This underscores the necessity of addressing marine litter impacts and enhancing knowledge and monitoring of less-studied litter types.

Materials and methods

We selected the islands of Vulcano, Lipari, Salina, Panarea, and Stromboli as test sites to monitor and assess plastic pellet pollution and to obtain data on their chemical composition and the impact of their degradation. In this paper, we present our sampling and analysis approach applied in the Aeolian Islands to enhance the understanding of the dynamics and impacts of plastic pellet pollution in this ecologically sensitive region. The sampled pellets were chemically characterized using Fourier transform infrared spectroscopy (FTIR), while surface alteration were assessed using stereomicroscopy. FTIR data underwent hierarchical cluster analysis (HCA) to reveal underlying relationships or groupings between sample features based on surface degradation characteristics.

Study site

The Aeolian Islands form an active volcanic archipelago with seven main islands and seamounts (Romagnoli et al. 2013; Peccerillo 2017), located in the southern Tyrrhenian Sea north of Sicily, in southern Italy. Geologically, they were formed by intense volcanic activity over hundreds of thousands of years during the Quaternary, spanning approximately from 250 to 300 ka to present (Lucchi et al. 2013; Peccerillo 2017). While the northern coasts are characterized by rugged morphology and small bays, the southeast shores facing Sicily are characterized by sheltered sandy beaches.

Five islands of the Aeolian volcanic archipelago were selected for this study: Lipari, Vulcano, Salina, Panarea, and Stromboli, located in the central and western sectors (Fig. 1). Alicudi and Filicudi were excluded as their beaches consist mainly of coarse gravel. Here below the descriptions of the sampled beaches:

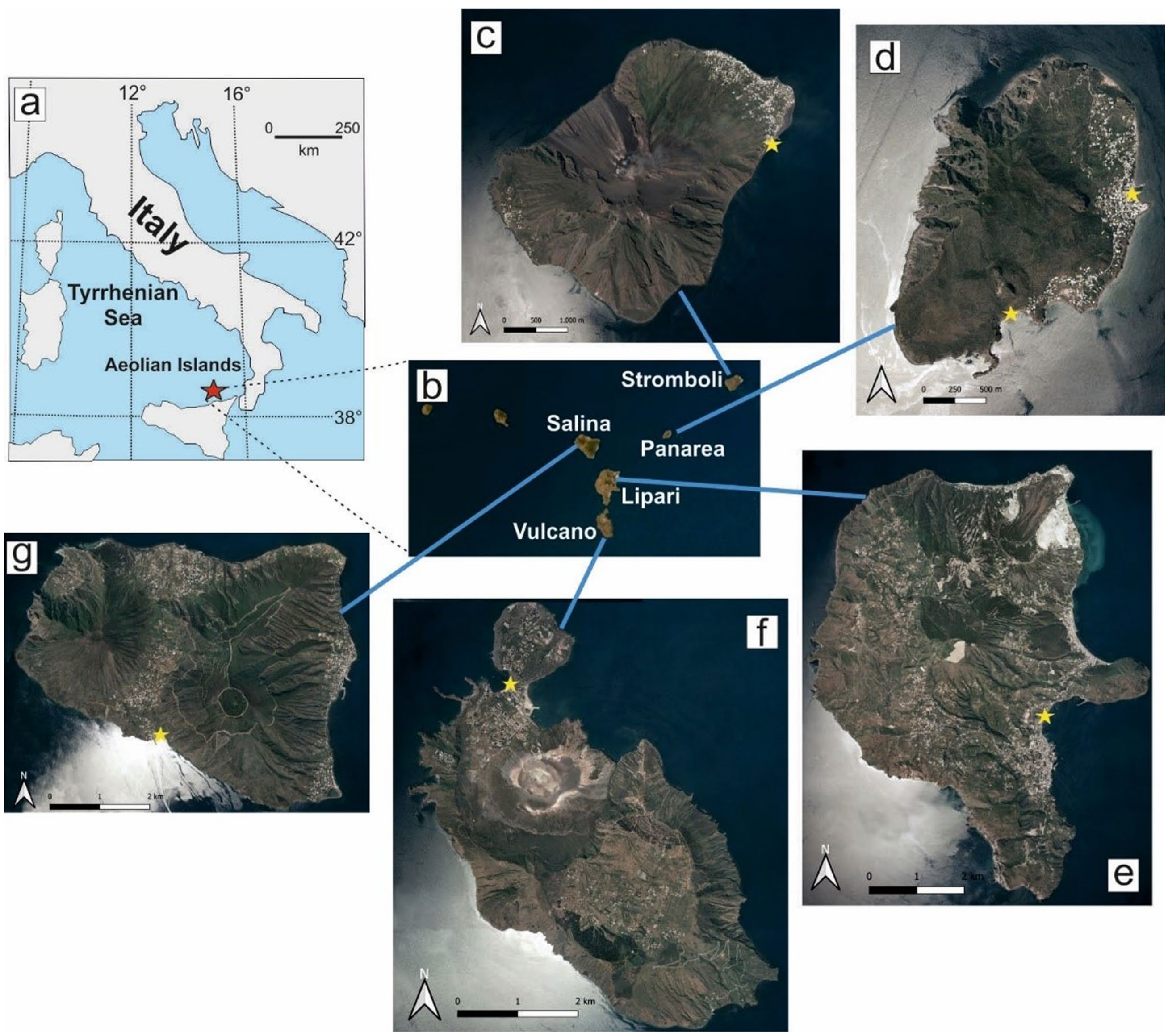


Fig. 1 **a** Map showing the location of the Aeolian Islands (marked by the red star) in the Tyrrhenian Sea, Mediterranean. **b** Map of the Aeolian archipelago with the individual islands labeled: **c** Stromboli, **d** Panarea, **e** Lipari, **f** Vulcano, and **g** Salina. The yellow stars on the island maps represent the sampling sites for plastic pellets in this study

Vulcano The beach "Sabbie Nere" (14°57′19.219 ″E, 38°25′6.786 ″N) is situated on the southeast coast of the island. This beach is notable for its unique medium to fine-grained black sand, composed of volcanic minerals, stretching approximately 800 m in length.

Lipari "Marina Lunga" beach (14°57′15.487 ″E, 38°28′18.923 ″N) is located on the southeast coast of the island. It consists predominantly of gravel and sand, extending for about 1 km in a wide crescent shape that offers partial protection from the waves. The seabed gently slopes near the shore, facilitating the accumulation of pellets and other detrital materials in shallow waters.

Salina The pellets were discovered on a small beach beneath the pier of Salina harbor (14°52′17.535 ″E, 38°33′29.064 ″N). This beach comprises gravel and sand, forming a small bay where sediment deposition is sheltered by the beach's enclosed shape, effectively protecting it from strong wave energy.

Panarea The beach "Cala Zimmari" (15°3′58.223 ″E, 38°37′43.807 ″N) is situated on the south side of Panarea Island, bordered to the southwest by the headland "Punta Milazzese." This "red beach" is characterized by fine-grained, red-colored sand, and features several detrital, fan-shaped deposits. "Panarea Porto" is located on the central and eastern coast of Panarea, the beach (15°4′37.127 ″E, 38°38′15.784 ″N) is short in length (about 40 m) and relatively narrow. It consists mainly of fine to medium-grained light brown sand, derived from the weathering and erosion of the island's volcanic bedrock.

Stromboli The beach of Scari (15°14′19.632 ″E, 38°47′49.854 ″N) is positioned on the eastern side of Stromboli Island, just below the village of Borgo San Vincenzo. It comprises two sections separated by a pier and is characterized by lava gravel and black sand, formed from volcanic ash and minerals deposited over time due to the island's volcanic activity.

Sample collection

In the coastal areas studied, the beach depth remained relatively stable due to the lack of significant daily tidal fluctuations. However, to minimize the potential influence of seasonal variations and fluctuating environmental conditions on particle accumulation rates, samples were systematically collected from all designated beaches over a span of two months, specifically from August to November 2023, using defined sampling transects.

During sampling, plastic pellets were collected from the uppermost 5 cm of sediment. To avoid contamination, the pellets were retrieved from the beach line using metal tweezers. The collected pellets from each site were then carefully stored in separate 50 mL glass centrifuge tubes for further analysis. Pellets were collected and analyzed from the following beaches: Panarea-Cala Zimmari with 30 samples, Panarea-Porto with 30 samples, Vulcano with 30 samples, Salina with 28 samples, Stromboli with 30 samples, and Lipari with 30 samples. A statistically significant amount of plastic pellets was collected at each site, ensuring the method's suitability for our objective, which included analyzing both spatial and temporal variability in sample abundance. Subsequently, all collected pellets were transported to the laboratory for chemical composition analysis and assessment of degradation using Fourier transform infrared spectroscopy and stereomicroscopy.

Laboratory analyses

The plastic pellets were comprehensively characterized by a combination of visual inspection and analytical methods. An initial macroscopic inspection allowed the description of key properties such as shape and color of each pellet. Then, individual pellets were carefully cut open so that both the core and the surface areas could be closely examined under magnification. A ZEISS AXIO ZOOM V16 stereomicroscope in conjunction with a digital camera facilitated the inspection of the pellets at the macro level and enabled the detection of visual features indicating degradation or change.

This methodological approach should provide information on how the chemical composition can vary within a single pellet. Chemical characterization was performed using Fourier transform infrared spectroscopy (FTIR) to identify the specific types of plastic polymers in the samples. The combination of microscopic examination and FTIR analyzes provided a comprehensive understanding of both the physical changes and chemical profiles of the plastic pellet samples.

To assess the degradation processes caused by composition and weathering in the marine environment, the color change or "yellowing" of the pellets was evaluated using the Yellowness Index (YI), derived from the color palette of Abaroa-Pérez et al. (2022). To investigate the degradation processes and chemical transformations of the plastic pellets, a hierarchical cluster analysis of the FTIR spectra was conducted.

Fourier transform infrared spectroscopy (FTIR)

Measurements were performed using an Agilent Cary 630 FT-IR spectrometer equipped with ATR sampling modules with a sampling press, single-reflection zinc selenide (ZnSe), and diamond. The plastic pellets were cleaned and prepared for FTIR-ATR analysis by soaking them in deionized water for 10 min. The spectra were collected in the 4000 and 650 cm-1 ranges with a resolution of 4.000 after 50 scans. The FT-IR spectra were baseline corrected and smoothed. This preprocessing was necessary to enhance resolution and interpretation by reducing noise and ghost peaks. The Polymer and Polymer Additives Library (supplied by AGILENT) was used to verify the polymer types and scans. Using the AGILENT database of plastic polymers and additives, the specific composition of each plastic pellet was determined.

Statistical analysis

Hierarchical cluster analysis (HCA) is a statistical method for grouping classes based on their similarity across multiple variables. It creates a hierarchical structure in which similar objects are grouped into clusters, which are then combined at higher levels of the hierarchy. The relationships between the different clusters can be visualized using a dendrogram. The hierarchical cluster analysis (HCA) performed in this study was based on the full FTIR spectral data, which ensured that all wavelengths and all bands of the functional groups were taken into account when creating the clusters. This approach allowed to determine the relationship between the chemical composition of the samples and their degree of degradation.

In HCA, Ward's minimum variance method was used to create homogeneous clusters with minimal deviation. This method aims to minimize the sum of squares within the clusters at each step of the clustering process. Specifically, the approach calculates the mean values for all variables within each cluster and then determines the squared Euclidean distance between each object and the cluster's mean values. These distances are summed for all objects within the cluster and the two clusters with the smallest increase in the total sum of squared distances are combined at each stage. This process continues until only one cluster remains. The result is a hierarchical structure that reflects the relationships between the different clusters.

The input to the HCA algorithm was an M-matrix of dimensions $n \times m$, with each row representing a spectrum and the columns representing the FTIR absorbance values at specific wavenumbers. The HCA algorithm treated each spectrum as a vector with components representing the intensities measured in the sampled spectral region and grouped the elements according to a similarity criterion calculated based on dissimilarities or distances between objects. By using the full spectrum FTIR data, the clustering was able to capture the relationships between the chemical composition and the degree of degradation of the polymer samples. This analysis categorized the pellets into distinct groups based on their degree of degradation aiming to gain a comprehensive understanding of the degradation processes and mechanisms.

Results and discussion

Pellets distribution and characteristics

A total of 180 pellets were collected on the beaches of the Aeolian Islands, although the quantities of pellets varied considerably at each sites:

- Panarea-Cala Zimmari had the highest density with 80 pellets/m^2 discovered on the surface; this higher density can be attributed to the unique location and geomorphology of the beach, which is characterized by a distinct indentation of the coastline.
- Panarea-Porto had a lower density of 30 pellets/m^2 on the surface.
- Vulcano had a density of 40 pellets/m^2 based on the 30 samples collected.
- Salina, Stromboli, and Lipari had densities of 20, 30, and 40 pellets/m^2 respectively, with 28 and 30 samples collected from each island.

These variations in pellet density reflect the heterogeneous distribution of plastic pellet pollution across the Aeolian Islands. The higher densities observed at Panarea-Cala Zimmari suggest the existence of localized pollution hotspots, possibly influenced by the geographical location and coastline morphology. It is hypothesized that the geomorphology and coastal dynamics of each sampling site play a significant role in shaping the distribution and accumulation patterns of the pellets.

In terms of color and shape, different types of plastic pellets were observed along the coastlines of the islands in the central and eastern part of the Aeolian archipelago. In general, spherical and disk-shaped pellets with a diameter of up to 2 mm and larger made up a large part of the collection. In addition to the typical spherical and disk shapes, other shapes such as cylindrical pellets and masterbatch (used in plastic manufacturing to carry pigments or other additives) were also found among the samples (Giugliano et al. 2022). Many pellets were transparent to translucent and colorless in appearance. However, some opaque and yellowish pellets were also present. Approximately 90% of the pellets collected ranged in color from white to yellow. The remaining 10% had other colors (see Fig. 2).

Polymer characterization

The interior of each pellet was analyzed ensuring that the data collected would remain uncontaminated and objective, unaffected by degradation processes that could

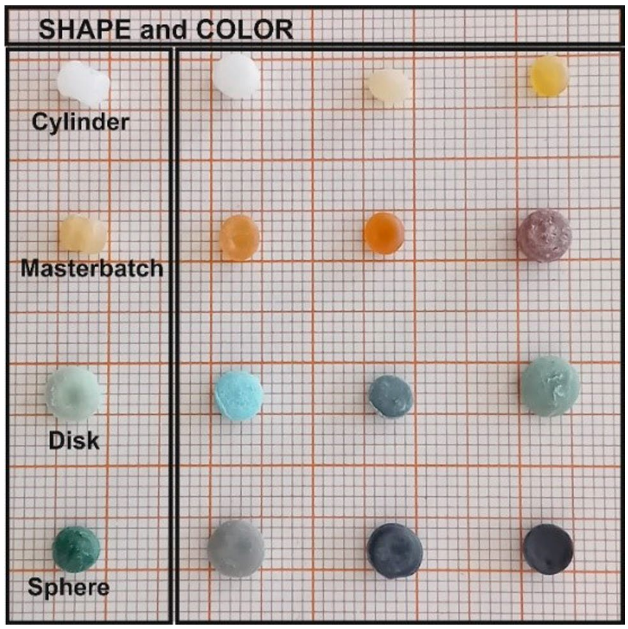


Fig. 2 Photos of plastic pellets collected on the beaches of the Aeolian archipelago. The selected particles show the different sizes, colors, and shapes representative of all the plastic pellets collected (Giugliano et al. 2022). White and light-yellow pellets accounted for most of the specimens found

potentially affect the outer surface of the pellets. Two polymers, polyethylene (PE) and polypropylene (PP), were identified (Fig. 3). Our results are consistent with previous studies conducted in the coastal areas of the Tyrrhenian Sea (Pedrotti et al. 2016; Caldwell et al. 2020; Piazzolla et al. 2023; Donato et al. 2024), which reported the composition and distribution of plastic pellet pollution at different beach sites along the Ionian and Tyrrhenian coasts, mainly characterized by the polymers polyethylene (PE) and polypropylene (PP).

Surface features

Stereomicroscopy was used to identify the mm-sized changes in the surfaces of plastic pellets caused by the effects of weathering and the marine environment. Examination under the microscope revealed that many of the pellets are rigid and have white, off-white, or yellowish pigmentation (Fig. 4). Many of the pellets examined have undergone a yellowing process, going from the white of virgin pellets to yellow, orange, or light brown. Previous studies have found that the color change or "yellowing" of plastic pellets indicates alteration processes and that the diversity of colors is determined by the composition and/or degree of weathering in the marine environment (Endo et al. 2005; Ogata et al. 2009; Fanini and Bozzeda 2018; Yamashita et al. 2018; De Monte et al. 2022). Jiang et al. (2021) interpreted the extent of weathering based on the yellowing index (YI) and the surface erosion area. Pellets with a YI ≥ 60% or a surface corrosion area ≥ 40% were categorized as weathered (Ogata et al. 2009; De Monte et al. 2022). Based on the color palette relating pellet color and YI (Abaroa-Pérez et al. 2022), 80% of the collected pellets ranged in YI values between 10 and 50%, while the remaining 20% are characterized by a YI ≥ 60%. Higher YI values (%) were attributed to a strong degradation of the microplastic samples due to the photooxidation process of the plastic (Da Costa et al. 2018; Chamas et al. 2020; Abaroa-Pérez et al. 2022).

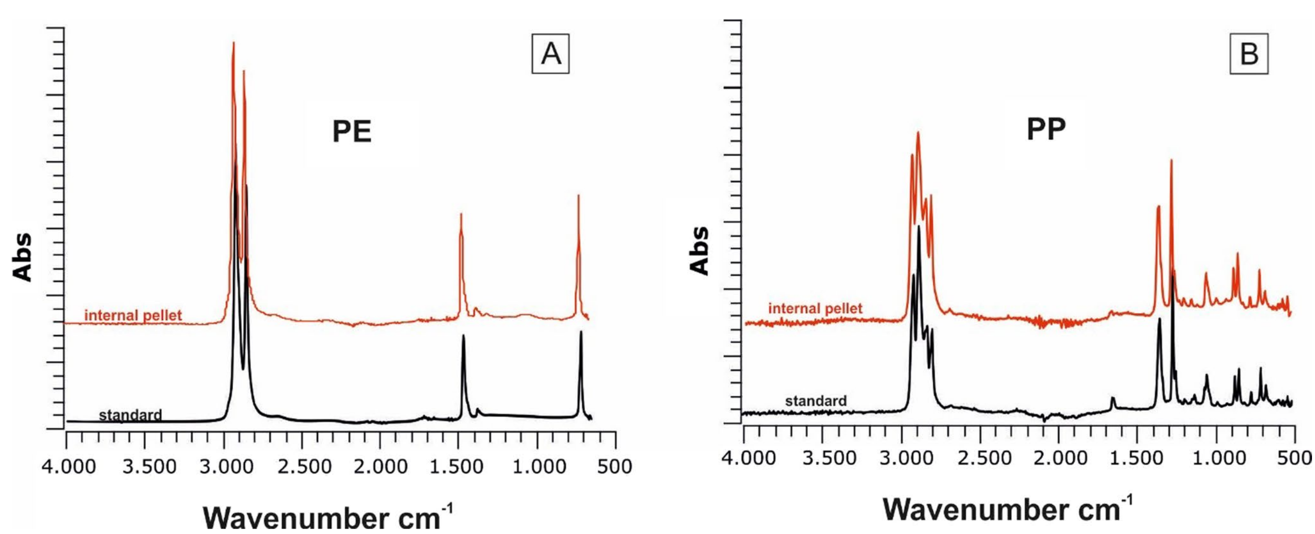


Fig. 3 FTIR-ATR spectra (red line) of PE (**A**) and PP (**B**) identified as representative of the composition of the inner part/core (red line) of all analyzed plastic pellets from the beaches of Vulcano, Lipari, Salina, Panarea, and Stromboli. Reference spectra (black line) of PE and PP were plotted for comparison

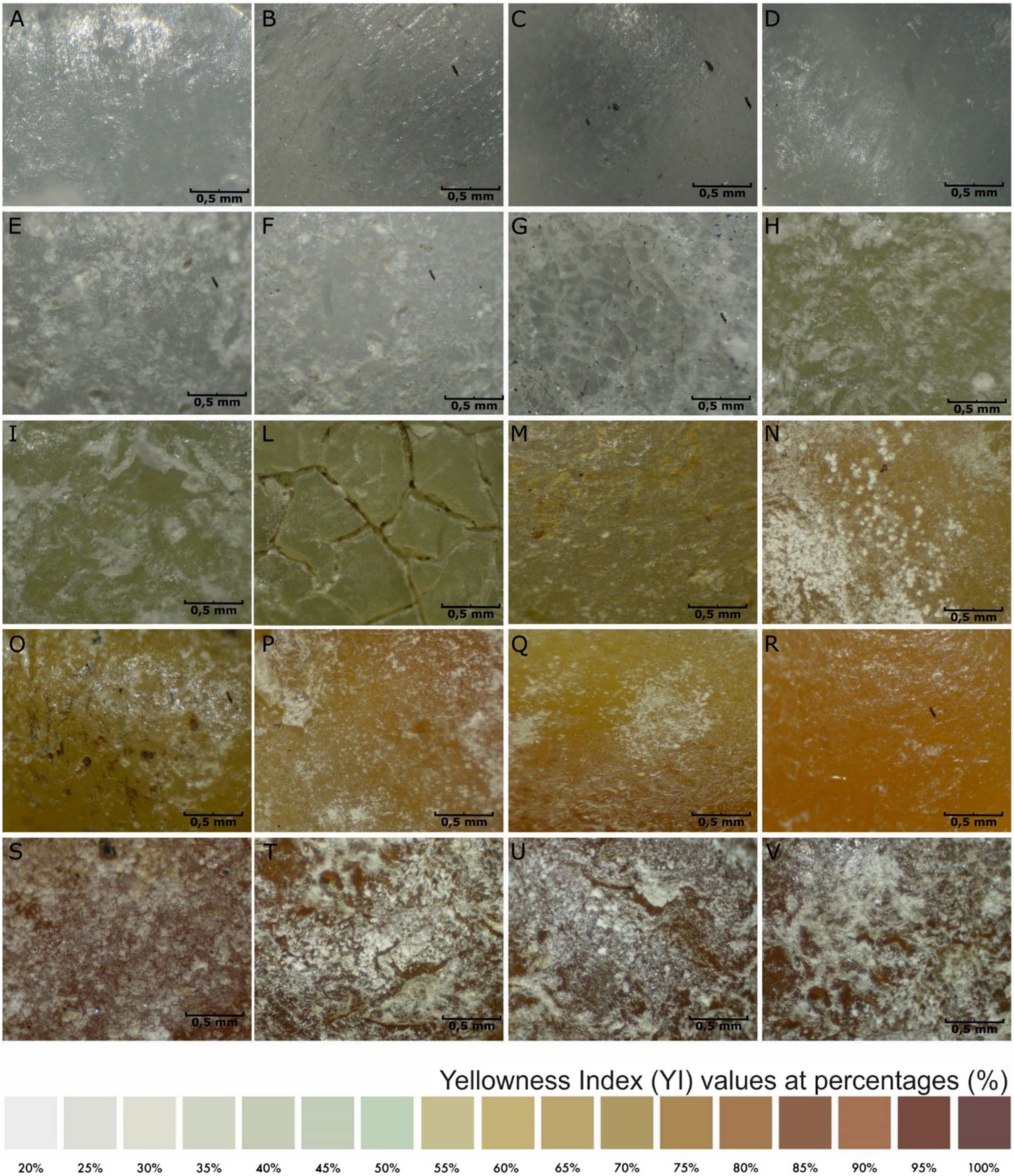
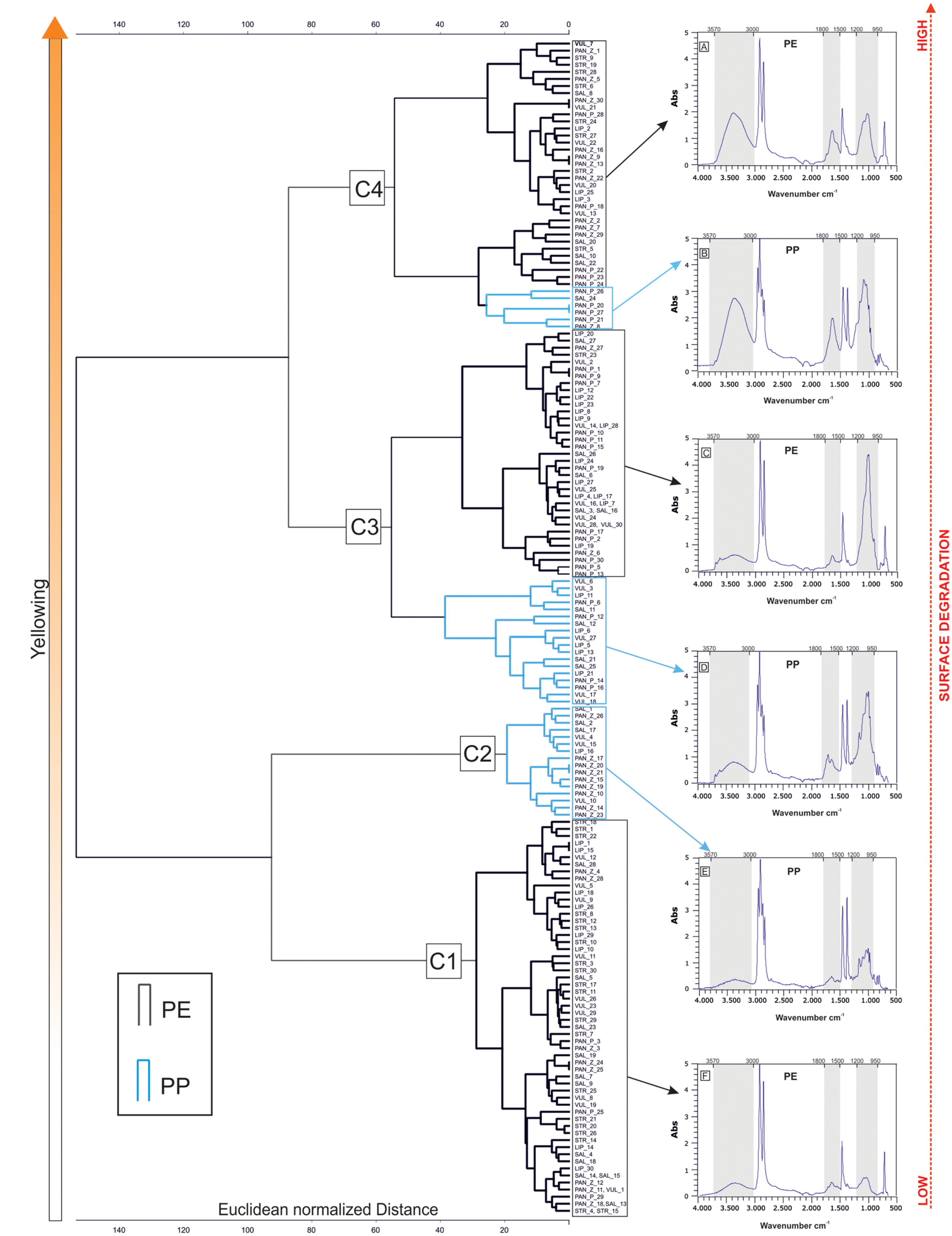


Fig. 4 Stereomicroscopic images showing the surface characteristics of plastic pellets collected from the beaches of the Aeolian Islands, characterized by an increase in the yellowing index. **A**–**G** Slightly to strongly degraded surfaces of white pellets; **H**–**R** different degrees of degradation of yellowed and orange pellets; **S**–**V** examples of strongly altered dark/brown surfaces of pellets. Figures **G**, **H**, **I**, **L**, **S**, **T**, **U** show fissured and broken surfaces. The color palette for the values of the yellowing index (%) from Abaroa-Pérez et al. (2022) is shown below the photos for comparison


Yellowing
Euclidean normalized Distance
140
120
100
80
60
40
20
0
C4
C3
C2
C1
PE
PP
A
B
C
D
E
F
Abs
Wavenumber cm-1
4.000
3.500
3.000
2.500
2.000
1.500
1.000
500
3570
3000
1800
1500
1200
950
HIGH
SURFACE DEGRADATION
LOW

◂**Fig. 5** Dendrogram of the hierarchical clustering analysis (HCA). Similarity: Euclidean normalized distance; method: Ward's linkage. The dendrogram clearly discriminates between groups of plastic pellets based on their degree of degradation, from low to high, identifies 4 main clusters C1, C2, C3, C4. A representative FTIR spectrum for the different groups identified has been included for clarity. The gray areas in the spectra show the changes in the hydroxyl, carbonyl, and carbon–oxygen chemical bonds during weathering. The left arrow indicates the progressive yellowing of the pellets, while the right arrow indicates the degree of their degradation

Different surface features provide valuable insights into the transformation and potential impact of plastic pollution in the marine environment. One of the most striking features is the fading of color as degradation progresses. Starting from the transparent pellets (Fig. 4A, B, C, D), there is a gradual shift toward increasingly degraded opaque yellow-orange-brown pellets (Fig. 4E/V). This transition is accompanied by changes in transparency, opacity, and light scattering properties, which have a significant impact on the visual appearance and potential ecological interactions of these degraded plastic pellets. The original bright colors fade over time due to prolonged exposure to sunlight and chemical reactions.

Another notable change is the development of surface roughness. As the plastic pellets degrade, their once smooth surfaces become rough (Fig. 4E, F, H, I), pitted (Fig. 4M, N, O, P, Q; Corcoran et al. 2009), and fractured (Fig. 4E, G, H, L, T, U, V), providing additional surface area for chemical reactions (e.g., hydrolysis, oxidation; Chamas et al. 2020) and probably microbial colonization (Fig. 4L, O). In addition, the constant exposure to waves and abrasive forces leads to surface erosion, which leaves visible abrasion marks on the surface of the plastic pellets (Fig. 4D, E, F). These erosive factors further contribute to the degradation process and affect the structural integrity of the plastic pellets. Finally, the formation of cracks (e.g., Fig. 4G, L) and fissures (e.g., Fig. 4I, T, U) on the surface of the degraded plastic pellets significantly increases their susceptibility to physical and chemical degradation (Abu-Hilal and Al-Najjar 2009). Ultraviolet (UV) radiation from the sun promoted oxidative degradation of the plastics, and the combined effects of this weathering and physical abrasion led to the formation of cracks and eventual embrittlement of the plastic pellets (Corcoran et al. 2009). These surface cracks act as points of attack for further degradation processes and can accelerate the fragmentation and release of microplastics into the marine environment.

HCA based on FTIR data to correlate chemical composition and degradation

FTIR analyses were performed on the surfaces of plastic pellets to investigate the molecular composition and detect signs of chemical degradation. The results showed remarkable variations in intensity and the appearance of specific absorption bands over the entire FTIR spectral range. These spectral changes served as evidence of molecular structural changes, including the breaking of bonds and the formation of new functional groups. Specifically, new absorption peaks appeared in the OH stretching region (at about 3400 cm^{-1}), between 1500 and 1800 cm^{-1}, which can be attributed to the stretching mode of the carboxyl groups (Fig. 5A). A large and intense peak between 850 and 1200 cm^{-1} (centered at about 1010 cm^{-1}) was observed in the Si–O stretching region. These peaks are associated with weathering (Brandon et al. 2016; Fernandez-Gonzalez et al. 2020; Tang et al. 2022; De Monte et al. 2022; Campanale et al. 2023). Plastic pellets from a particular group contained peaks for hydroxyl groups from broad central peaks at 3350 cm^{-1} (R – OH) and 1100 cm^{-1} (C – O) belonging to a mixture of primary, secondary, and tertiary alcohols. Infrared spectroscopy revealed peaks at 1640 cm^{-1} and 910 cm^{-1}, indicating vinyl molecular groups in the pellet samples. It is noteworthy that only a few clearly defined peaks were detected between 1650–1750 cm^{-1}, indicating that only a small enrichment of carbonyl groups (C–O) has taken place.

Three likely areas for weathering-related changes in the infrared spectra have been identified from previous studies (Socrates 2004; Pavia et al. 2008; Rajakumar et al. 2009; Brandon et al. 2016; Biber et al. 2019; De Monte et al. 2022): Hydroxyl groups (broad peaks from 3100 to 3700, centered at 3300–3400 cm^{-1}), alkenes or carbon double bonds (1600–1680 cm^{-1}) and carbonyl groups (1690–1810 cm^{-1}, centered at 1715 cm^{-1}). The increase in the absorption signal in the spectral range from 1000 to 1400 cm^{-1} in the FTIR spectrum of the carbonyl group was associated with the photo-oxidative process to which the polymeric material is subjected (Cai et al. 2018; Biber et al. 2019; Chamas et al. 2020; Abaroa-Pérez et al. 2022).

In order to categorize the plastic pellets according to their degree of degradation, a hierarchical cluster analysis was performed. By comparing the FTIR spectral features of all analyzed pellets, characteristic changes in the intensity and position of the absorption bands could be observed. These changes provided insight into the degradation processes, such as oxidation, hydrolysis, and fragmentation, and allowed a comprehensive understanding of the chemical composition and structural integrity changes that occur during the degradation process. This statistical method proved to be effective in identifying different clusters corresponding to different degradation phases. The resulting dendrogram (Fig. 5) illustrates the relationships between the identified clusters. There are several distinct clusters, with each group containing data points with similar spectral profiles. The hierarchical structure shows larger clusters at the top, containing subsets of smaller, finer clusters further down. The clear separation between the clusters indicates that they contain distinctly different data points, which facilitates interpretation of the underlying patterns and allows meaningful comparisons to be made. Four distinct clusters were identified, namely C1, C2, C3, and C4, as shown in Fig. 5. Cluster C1 comprises pellets with minimal degradation, indicating a relatively well-preserved condition. C2 and C3 represent an intermediate level of degradation with moderate changes. In contrast, C4 includes significantly degraded samples. A representative FTIR spectrum was assigned to each identified cluster, showing the characteristic peaks of change.

In addition, the analysis revealed specific degradation patterns that are unique to different polymer types. Polyethylene (PE) pellets showed a gradual decrease in the intensity of C–H stretching vibrations as degradation progressed, indicating a progressive chain break. The appearance of carbonyl (C = O) absorption bands indicates oxidation and the formation of new functional groups within the polymer structure. These changes indicate chemical reactions such as chain scission and oxidation processes leading to fragmentation and degradation. In contrast, there was a progressive increase in the intensity of the C–H bending vibrations, indicating changes in the molecular structure. This increase indicates chain scission and the formation of shorter polymer chains. In addition, new absorption bands related to oxidation appeared, indicating oxidative degradation. The changes in surface morphology varied between seawater and sand exposure. Samples immersed in seawater developed porous textures, while pellets stored in sand did not exhibit this change (De Monte et al. 2022). These differences correlate with chemical changes in the polymer chains on the surface of the pellets due to the marine conditions. Seawater accelerates both physical and chemical degradation processes, including abrasive hydraulic effects, hydrolysis, and accelerated photodegradation, which are more pronounced compared to when pellets are temporarily buried in sand (De Monte et al. 2022).

The carbonyl (CI) and vinyl (VI) indices were calculated for all analyzed pellets (see supplementary material) to corroborate the results of the HCA analyses. These indices are used to characterize the degree of weathering and surface oxidation in polymers (Bayo et al. 2022). In particular, the most degraded groups C3 (Tab. 1S) and C4 (Tab. 2S) identified in the dendrogram showed CI values between 0.34 and 1.80 and VI values between 0.45 and 1.56 for the PE pellets. In contrast, the less degraded groups C1 and C2 showed lower values for both indices. In particular, the PP pellets of the C2 group (Tab. 3S) had CI values between 0.18 and 0.50 and VI values between 0.13 and 0.35. The C1 group (Tab. 4S), which consisted exclusively of PE pellets, showed the lowest degradation with CI values between 0.02 and 0.35 and VI values between 0.02 and 0.24. The values of the two calculated carbonyl and vinyl indices confirm and support the results of the cluster analyses.

All the data obtained show that the plastic pellets found at the Aeolian sites exhibited varying degree of degradation. Most pellets showed only minimal signs of degradation, suggesting limited exposure to physical weathering processes. However, other pellets displayed significant changes in chemical composition and physical properties, indicative of different degradation pathways. In addition, the yellowing observed in some pellet samples is likely attributed to solar radiation in the marine environment, a common factor contributing to the degradation of plastics (Abaroa-Pérez et al. 2022). The range of decomposition observed among the pellet samples indicates the variety of weathering and degradation processes occurring in coastal environments. This highlights the complex and dynamic nature of plastic pollution in marine settings, where pellets can undergo different degradation pathways influenced by environmental factors.

Challenges in tracing the provenance of plastic pellets in the Aeolian Islands

Given the complexity of the factors involved, it is difficult to determine the exact origin of the plastic pellets found on the coast of the Aeolian Islands. The islands do not host local plastic pollution facilities, eliminating then as direct source. However, there is extensive plastic production and processing on the Italian mainland (ECCO-Climate Technical Report 2022). The plastic industry sector manufactures finished plastic products from imported polymers, most of which are imported in the form of plastic pellets. The waste management and disposal practices associated with the production and processing industrial activities, and therefore the possible sources of pellets in seawater, are not fully understood. One plausible source could be the Tyrrhenian Sea, which serves as an important transport and transshipment center in the Mediterranean region. It is likely that untreated plastic pellets are imported, exported, stored, and transhipped through this sea area as part of larger supply chains and logistics networks. Accidental spills or leaks during these transport activities could release the pellets into the marine environment (Karlsson et al. 2018). Apart from the Italian plastics industry, the proximity of the Aeolian Islands to the western Mediterranean Sea raises the possibility that plastic pellets from production facilities in other countries bordering this sea could also contribute to the observed pollution. The almost closed nature of the Mediterranean Sea, combined with the persistent input of litter from rivers, land, and the atmosphere further complicates efforts to determine the origin of this pollution (Millot and Taupier-Letage 2005; Hanke et al. 2013; Pedrotti et al. 2022). Given the ubiquity of plastics in the Mediterranean

Sea (Morales-Caselles et al. 2021), it is likely that the plastic pellets in the Aeolian Islands originate from a combination of sources throughout the region rather than from a single, identifiable point of release. The near-enclosed nature of the Mediterranean restricts the movement of surface water, resulting in a constant input of debris from estuaries, overland rivers, and winds into the continental shelf area (Hanke et al. 2013; Pedrotti et al. 2022). Plastics make up more than 80% of the observed marine litter and represent the largest proportion of floating litter in the ocean, sometimes accounting for up to 100% of items (Morales-Caselles et al. 2021). This contrasts with the predictable patterns of plastic accumulation in oceanic gyres, where circulation patterns can be used to identify sources. In the Mediterranean Sea, the strong seasonal variability and intense mesoscale activity of surface currents prevent the formation of stable areas where plastic can concentrate (Millot and Taupier-Letage 2005; Pedrotti et al. 2022). Several models have suggested that seasonal plastic accumulation is influenced by proximity to sources such as large cities and rivers (Zambianchi et al. 2017; Liubartseva et al. 2018). However, these models do not match the field data. The isolated geographical location of the Aeolian Islands, combined with the complex circulation patterns (currents and winds) of the Mediterranean Sea, makes it particularly difficult to clearly identify the specific sources of the plastic pellets found along their coasts.

Addressing plastic pellet pollution in the Aeolian Islands: proposed mitigation strategy

Our research shows that plastic pellet pollution is affecting the Aeolian Islands, a well-known Italian island archipelago. While sampling the coasts of Lipari, Vulcano, Salina, Panarea, and Stromboli, we encountered plastic pellets at every site we visited. During manual sieving of sand, plastic pellets were found frequently embedded in the sampled fine coastal sediments. Preliminary analysis indicates that pollution is widespread across the archipelago, with particularly high levels observed on some islands, such as Panarea.

The presence of plastic pellets in these coastal areas is significant a cause for concern. They pose a danger to marine life and seabirds that may ingest them, reflecting a broader issue for plastic pollution affecting these fragile coastal habitats. Marine fauna are particularly vulnerable, as ingesting pellets, mistaken for food, can lead to intestinal blockages or internal injuries (Tuuri and Leterme 2023; Jiang et al. 2023). To address this threat and understand the extent of plastic pellet pollution in the marine environment, future research needs to focus on monitoring and assessing the distribution of plastic pellets in marine sediments through comprehensive marine surveys. By studying the presence and distribution of pellets in marine sediments, researchers can gain valuable insights into the extent of the problem and develop targeted strategies to combat plastic pollution in the Aeolian Islands and protect the health of marine ecosystems. Our study sheds new light on the urgent action needed to curb the discharge of plastic pellets and microplastics at its industrial sources. If plastic pellet pollution is not curbed, it will jeopardize the very features that led to the islands' World Heritage designation, namely their natural beauty, endemic wildlife, and balanced marine ecosystems.

To mitigate this plastic pollution threat, coordinated action at multiple levels is urgently needed. Regional cooperation between municipalities and national governments, guided by the EU Marine Strategy Framework Directive, can effectively tackle the problem. Waste reduction must be a priority and strategies such as taxing single-use plastics can help reduce the amount of waste entering the marine environment. At the local level, strict guidelines for managing plastic waste, controlling sources of release, and raising awareness of the dangers of littering among residents and tourists are essential. Beach clean-ups, the installation of sand fences and public education campaigns on the proper disposal of waste and the handling of pellets can strengthen long-term habitat management. At a global level, promoting more sustainable practices in the plastics industry, supporting the circular economy, and developing biodegradable polymers are necessary. These efforts, in combination with engagement activities, can bring about behavioral change in island communities.

Conclusions

The coastline of the Aeolian Islands is an important area for studying the distribution and structural properties of stranded plastic pellets. In this framework, we investigated the distribution and composition of plastic pellet pollution on the beaches of five of the Aeolian Islands in the Tyrrhenian coast. Through visual inspection and FTIR, we were able to identify the physical properties and polymer composition of the pellets.

The beaches of the Aeolian Islands, a UNESCO World Heritage Site, are heavily polluted with plastic pellets. The FTIR analysis revealed that 80% of the plastic pellets are made of PE and 20% of PP, the main polymers used in the plastics industry. The extent of pollution varied from island to island, with the highest concentrations found on Panarea, suggesting that the strong seasonal variability and intense mesoscale activity of surface currents, together with the geographical location of the beaches studied, influence the distribution of plastic pellets. Our study highlights the different characteristics resulting from the degradation of plastic pellets at the surface. Changes in optical properties, color fading, surface roughness, erosion, and cracking all contribute to the complex dynamics of plastic pollution in marine ecosystems. Morphological analysis showed clear signs of degradation in some pellets, such as yellowing and changes in opacity, which may affect their toxicity and fate in the environment. Hierarchical cluster analysis (HCA) proved to be a suitable statistical method for analyzing the FTIR spectral data and effectively identified different clusters reflecting different stages of pellet degradation. It should be noted that the accumulation of pellets may be subject to seasonal and cyclical variations related to weather events and periods of rough seas. As a remote archipelago, the Aeolian Islands serve as a natural laboratory to study the effects of microplastics in presumably unpolluted areas. Monitoring pellet quantities, characterizing their composition and degradation is crucial for assessing the associated risks and supporting mitigation strategies. Protecting this biodiversity hotspot, a cradle of natural beauty and exceptional biodiversity, requires a holistic approach that considers the interrelationship between human pressures, the health of marine ecosystems and conservation efforts simultaneously.

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Availability of data and materials The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

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