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Spatial distribution of macro- and micro-litter items along rocky and sandy beaches of a Marine Protected Area in the western Mediterranean Sea

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ABSTRACT

In this study, the spatial distribution and physical characteristics of beach macro- and micro-litter within the Cabrera Archipelago Maritime-Terrestrial National Park (Cabrera MPA), in the Balearic Islands have been analysed. For macro-litter items, a mean concentration of 1.9 ± 2.4 items/m^2 weighing a total of 13 kg was quantified. In terms of beach composition, cobble beaches with deposited seagrass had almost twice as much marine litter as other beaches. For beach micro-litter items, white and transparent microplastics within the size class of 1–2 mm were the most abundant on all the beaches, and the most common polymer types were polyethylene (64%) and polypropylene (17.2%). Overall, for both macro- and micro-litter items, plastic was the most dominant material (90%) identified on all beaches surveyed within Cabrera MPA, indicating areas of low anthropogenic pressures are increasingly becoming sinks for marine litter.

1. Introduction

Marine Protected Areas (MPAs) in the Mediterranean Sea are not exempt from human impacts which range from coastal activities (recreational and professional) and resource exploitation to climate change, invasive species and pollution (Coll et al., 2012, 2010). Increased reporting and scientific evidence has initiated growing attention to the impact of marine litter (ML), primarily of plastic origin, on the marine environment, as its presence has shown to generate social, economic and ecological impacts at a local and global scale (UNEP, 2016). In the Mediterranean Sea, ML has been found to be accumulating on beaches and seafloor areas and floating on the sea surface (Alomar et al., 2020a; Compa et al., 2020; Martinez-Ribes et al., 2007; Suaria et al., 2016; Vlachogianni et al., 2017). Moreover, impacts of ingestion, colonization and entanglement to marine diversity have been reported, threatening the overall health of marine ecosystems (Alomar et al., 2020b; Compa et al., 2019a; Deudero and Alomar, 2015).

Globally, beaches have been highlighted in ML studies as accumulation areas, whether frequented by visitors or found in the most remote regions protected from almost all human activities (Lavers and Bond, 2017; Waluda et al., 2020). In addition to empirical evidence, numerical models have highlighted that Mediterranean MPA coastlines are receiving plastic pollution through various daily coastline fluxes (Liubartseva et al., 2019). Results from these studies emphasize the reporting of ML pollution in MPAs is not unique despite their protected status, due to the positive buoyancy of many ML items which can be transported by ocean currents and winds from source to sink areas. Additionally, given the longevity of these litter items, with lifespans of decades, they often become embrittled from UV and wave exposure, breaking or fragmenting into smaller items and ending up on the beaches and coastal areas (Andrady, 2011; Barnes et al., 2009).

The Balearic Islands are located in the western Mediterranean Sea between the Algerian Current to the south and the Northern and Balearic Currents to the north (Balbin et al., 2014). In regards to ML, the Balearic Islands area is a hotspot for ML, especially plastics that have been found in abundance on the seafloor (Alomar et al., 2020a), in the gut contents of marine organisms (Alomar et al., 2020b; Alomar and Deudero, 2017; Nadal et al., 2016; Rios-Fuster et al., 2019), floating on the sea surface (Compa et al., 2020, 2019b) and accumulating on sandy beaches (Martinez-Ribes et al., 2007). There are several MPAs in the Balearic Islands and the Marine Protected Area of Cabrera Archipelago Maritime-Terrestrial National Park (Cabrera MPA) has a sea perimeter of almost 900 km^2 with a few small sandy beaches although the shore is mainly rocky with small inlets. It has various degrees of protection to limit public access in order to preserve the endemic and endangered species as well as habitats of ecological importance (Habitats Directive 92/43/EEC). Currently, this MPA is accessible year-round to recreational and charter/tour boats, which must stay within the limits established by the

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MPA in addition to acquiring permissions where they are needed depending on the purpose of the visit and is currently managed by the local government of the Balearic Islands. The study of coastal areas including sandy beaches not only provides a snapshot of the accumulation of different types of ML arriving to this protected area, but also insights into litter sources.

Consequently, due to the ecological and biological importance of coastal areas and the interface between sea and land which they represent, identification and analyses of the spatial abundance and distribution of ML and microplastics along beaches within MPA is important. Thus, the aims of the study are to: i) identify the abundance of ML along the beaches in no-take areas and public access areas, and the factors that influence its spatial distribution, ii) quantify the abundance of the micro-litte items in the sediments of these beaches, and iii) characterize all quantified items in terms of size, shape, colour, and polymer type. Results from this study will aid at identifying and understanding potential sources of ML deposited in the study area to address feasible mitigation measures.

2. Materials and methods

2.1. Study area

Macro- and micro-litter surveys were carried out on 6 beaches within Cabrera MPA from the 29th of July to the 10th of August and on the 29th and 30th of October in 2019 (Fig. 1). Two of the beaches (Cala en Ganduf and Es Caló des Forn) were located within the no-take area of the bay of Santa Maria which is a marine reserve and public access is strictly prohibited both by land and sea (Fig. 1A). The other four beaches (S'Espalmador, Sa Platgeta, Sa Platgeta des Pages and Es Caló des ses Guïes; Fig. 1B) were located within the port area of the island of Cabrera which is mainly accessible to the public. Considering the small size of the beaches on the island, the sampling unit of the beach was considered to be the whole beach adopted from the Plastic Busters MPAs protocols (Fossi et al., 2019).

The number of people involved in the surveys was dependent on the beach and season varying from 1 to 17 people per survey (Table 1). The area of each beach was calculated as the entire length of the beach and width from the shoreline to the backshore, and environmental characteristics of the beach such as beach type and beach orientation were recorded. The smallest beach was Es Caló de ses Güies covering an area of 95.9 m^2 and is restricted to public access although it is located within the port area of the Port of Cabrera. The largest beach was Sa Platgeta located within the port area covering an area of 479.5 m^2 and the public is allowed access to this beach.

2.2. Beach surveys and ML classification

For macro-litter sampling, the monitored sites were selected taking into account areas affected by human activities and protected no-take areas. All visible non-organic items from the sampling site were collected and transported to the laboratory located in Cabrera MPA. All ML items were categorized in situ following the harmonized protocols from the Plastic Busters MPAs project (Fossi et al., 2019). This protocol is an adaptation of the Technical Group Marine Litter (TG ML) for the Marine Strategy Framework Directive document (Galgani et al., 2013; Fleet et al., 2021), and a total of 11 main litter categories are considered: artificial plastic polymers, rubber, ceramics, processed/worked wood, metal, paper/cardboard, paraffin/wax pieces, medical waste, sanitary waste, clothing/textile, and glass, which were then classified and assigned the TG ML General Code, weighed to the nearest two decimal points (grams) and assigned one of the following size classes: A = 25 cm^2, B = 100 cm^2, C = 400 cm^2, and D = 2500 cm^2. Items larger than <2500 cm^2 were not found on any of the beaches surveyed.

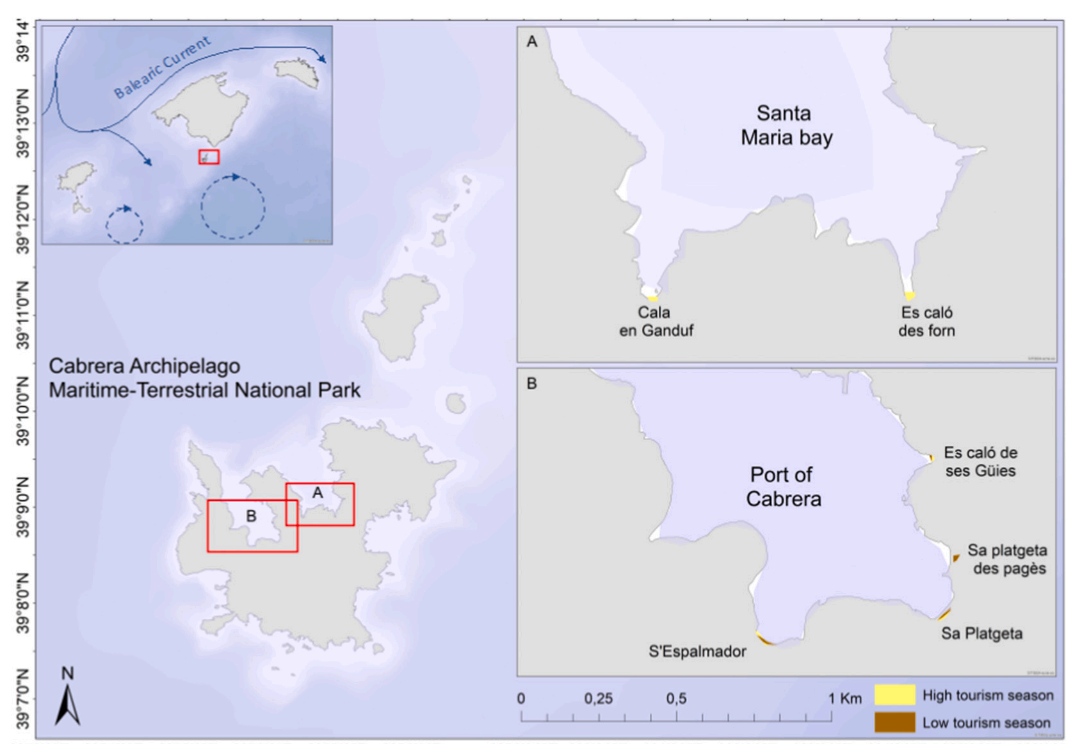

Fig. 1. Map of the study area for beach surveys carried out in 2019 within the Bay of Santa Maria (A) and the Port area of Cabrera National Park (B). Yellow areas indicate surveys carried out during high tourism season and brown areas indicate surveys carried out during low tourism season. In the inset map, the Balearic Current is shown in thick dark blue arrows and the Algerian gyres are shown as dashed dark blue arrows (adapted from Balbin et al., 2014). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Summary of the beach marine litter surveys according to tourism season, beach type, public access, beach orientation, surveyed area, number of micro-litter samples, and number of surveyors.

Location	Beach name	Tourism season	Beach type	Public access	Orientation	Surveyed Area (m^2)	Number of micro-litter samples	Number of surveyors
Es Port	Sa Platgeta	Summer/high	Semi-rural	Public access	S-W	479.5	9	1
Es Port	Es caló de ses Güies	Summer/high	Semi-rural	Restricted	S-W	95.9	6	1
Es Port	S'Espalmador	Summer/high	Semi-rural	Public access	N	383.6	4	1
Santa Maria	Cala en Ganduf	Summer/high	Remote/natural	Restricted	N	239.7	5	2
Santa Maria	Es Caló des Forn	Summer/high	Remote/natural	Restricted	S-W	383.6	4	2
Es Port	Sa Platgeta	Autumn/low	Semi-rural	Public access	W	335.6	NA	11
Es Port	Es caló de ses Güies	Autumn/low	Semi-rural	Restricted	S-W	95.9	NA	2
Es Port	S'Espalmador	Autumn/low	Semi-rural	Public access	N	440.6	NA	9
Es Port	Sa Platgeta des pagès	Autumn/low	Semi-rural	Restricted	S-W	316.5	NA	17

2.2.1. Clean-Coast Index

In addition to the classification of the marine litter, the Clean-Coast Index (CCI) was calculated in an attempt to measure the progress and success from the clean-up efforts from the summer to the fall season. This index was calculated as: CCI = CM * K, where CM is the abundance of ML (items/m^2) and K is a constant equal to 20 (Alkalay et al., 2007; Vlachogianni et al., 2018). According to this index, beaches were classified as very clean (0–2 CCI), clean (2–5 CCI), moderately clean (5–10 CCI), dirty (10–20 CCI), and very dirty (>20 CCI).

2.2.2. Macro-litter data analyses

To determine which factors contribute to the abundance of marine litter on beaches in Cabrera MPA, nonparametric Kruskal-Wallis tests were considered for the following factors: size class of items (A, B, C, D), beach orientation (N, S-W, W), material type (artificial polymers, cloth/textile, glass/ceramics, metal, paper/cardboard, processed/worked wood, rubber, unidentified), and beach composition (cobbles and sand, sand, cobbles, and cobbles and seagrass). For tourism season (high and low) and beach accessibility (permitted/restricted), a Mann-Whitney *U* Test was performed to assess for ML abundance. For significant factors, a post-hoc analysis with a pairwise Mann-Whitney Wilcoxon test was performed to determine specific differences between the groups. Prior to any analyses, a non-normal distribution was confirmed via a Shapiro-Wilcox test. For all tests, significance was established at $p \leq 0.05$.

The next step was to evaluate the spatial distribution of marine litter on beaches using a Generalized Linear Model (GLM) to identify the combined factors that lead to the accumulation of marine litter. For the fixed factors, the following factors and their coefficients were considered: size class of items, site, material type, beach accessibility, beach orientation, beach composition and tourism season. A negative binomial distribution model was performed including the spatial area of the beach as an offset, given that the Poisson distribution model was found to be over-dispersed. The initial model considered all possible contributing factors and model selection was performed using a stepwise approach, and the model with the lowest AIC deemed the best-fit model. The residuals of all final models were inspected for normality.

2.3. Sediment surveys

Beach sediment samples were collected from each of the six beaches surveyed in August 2019. Considered the relatively small size of the beaches, between 4 and 9 sediment samples were collected depending on the beach, and when possible, between 2 and 3 samples were collected from the shoreline at the foreshore, mid-shore, and backshore. The first 5 cm of the surface sediment was collected using a 0.25 × 0.25 m quadrant and stored for further analysis in the laboratory.

2.3.1. Sediment granulometry analysis and microplastic separation and identification

Granulometric analysis was performed by mechanical shaking using a stack of sieves considering three size fractions: >5 mm, 2–5 mm, and 1–2 mm. Each sample was dried at 60 °C for 48 h before mechanical sieving to ensure that all moisture had been removed from the sample. Once dried, each sample was placed on the uppermost sieve fraction, corresponding to the 5 mm size class, and mechanically shaken for 10 min. For each separated size fraction, all MPs were visibly sorted and characterized under a stereomicroscope (Euromex NZ 1903-S) with optical enhancement from 6.7× to 40.5× and with an attached CMEX 3.0 MP camera using a calibration software, Image Focus® 4.0 (Euromex software). Identified items were classified by shape (pellet, fragment, fibre, film, rope and filaments, microbeads, styrofoam (expanded polystyrene-PS), and rubber) and colour (black, blue, white/transparent, white/opaque, red, green, multicolour, other) following the Plastic Busters MPAs framework (Fossi et al., 2019).

2.4. FTIR- ATR

The polymer characterization of macro- and micro- litter items was analysed using Fourier Transform Infra-Red – Attenuated Total Reflectance (FTIR-ATR) using a Bruker 800. For the sediment samples, accounting for the considerable abundance of items at several of the beaches, a subset of 10 items from each size fraction was randomly selected to be determined via FTIR-ATR. The identification of each polymer was compared with several spectrum databases (Löder et al., 2015, BASEMAN D1_2 and in-house generated libraries) for polymers including high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyamide (PA), polyester (PES), polypropylene (PP), polystyrene (PS), acrylonitrile-butadiene rubber (ABR), acrylonitrile butadiene styrene (ABS), styrene – acrylonitrile (SAN), styrene butadiene rubber (SBR), paint (PT), cotton, latex, and silicon. The wavenumber range of 400–4000 cm^{-1} was used for measurements and 8 scans were performed per item and all items identified with a quality hit index of >700 (max 1000) were considered confirmed polymers and spectra comparison was done with the Opus 6.5 software and (Fagiano et al., 2022).

2.5. Micro-litter data analysis

For the micro-litter sediment samples, a Kruskal-Wallis test was performed to identify whether there were differences in abundance between beaches and survey transect sample. Additionally, to identify differences in item characteristics found at each surveyed site and sediment samples, a non-metric multi-dimensional scaling (nMDS) was performed to visualize data segregations for size, shape, colour and polymer type for each sediment sample. Moreover, a multivariate ANalysis Of SIMilarity (ANOSIM) one-way test was performed to calculate significances running at 9999 permutations. All data analysis was performed in R version 3.6.2 (R Core Team 2019).

3. Results

3.1. Beach surveys

3.1.1. Abundance and composition of macro-litter

All surveyed beaches contained macro-litter with a mean abundance of 1.9 ± 2.4 items/m^2 weighing a total of 13 kg. The highest abundance of marine litter was reported during low tourism season at the beach of Sa Platgeta des Pagès (5.8 items/m^2; 8.3 g/m^2) and Es Caló de ses Güies (4.7 items/m^2; 5.2 g/m^2) (Table 2). The beaches with the lowest reported abundance of ML were S'Espalmador (0.3 items/m^2; 1.2 g/m^2) and Caló des Forn (0.3 items/m^2; 1.2 g/m^2), both during the summer and the low tourist season. In terms of items/100 m, Es Caló des Forn in the bay of Santa Maria had the lowest overall amount (439.8 items/100 m, median) while Es Caló de ses Güies in the port had the highest abundance (1349.3 items/100 m, median). Following the CCI, four of the beaches sampled in the summer were considered moderately clean or dirty, while Es Caló de ses Güies was classified as very dirty with an ICC of 57.77 (Table 2). The contrary was found during low tourism season in the autumn where all of the surveyed beaches fell within the category of very dirty, with their CCI's increasing and in the case of S'Espalmador, its CCI increased almost 5-fold.

According to the results of this study for both sampling surveys, more than 90% of the items were assigned within the category of artificial polymer materials and the second most common category was glass/ ceramics at 6.6% and the remaining categories were less than 5% of all identified items. In terms of survey seasons, a similar pattern was observed during the summer survey (Fig. 2A) where consistently on all beaches artificial polymers were >90% of items surveys. During the fall survey at the S'Espalmador beach in the port area for example, glass and ceramics comprised over almost 20% of the collected items and were overall the second most common item (Fig. 2B). Of the artificial polymers found, almost 25% of the items (1005 items) were classified as G79-Plastic pieces 2.5 cm >< 50 cm, and G21-Plastic caps/lids from drinks (373 items: 9.13%) was the second most common category accounting for almost 10% of the identified litter items, followed by G95-Cotton bud sticks at 7% (292 items) (Table 3). Of the remaining categories, although they were not as common, their abundance was notable, and various items consisted of remnants from food containers, pieces of fishing nets, plastic sheeting, foam sponges, and other plastic identifiable items such as plastic clothes pins were observed. Glass and ceramic fragments were the 5th most common category comprising for less than <7% of the total amount of litter quantified in beaches of Cabrera MPA.

For the different factors considered, by size class (volume), an average of 2.4 ± 2.6 items/m^2 were collected from the smallest size class (A) and the least common size class were items classified as class D, the largest size items (0.02 ± 0.02 items/m^2) (Fig. 3A). Significant differences were found between the two largest size classes C and D compared to the smaller size classes (KW, $p < 0.001$). In terms of the season, higher concentrations were found (3.4 ± 2.15 items/m^2) during the low tourism season compared to the high tourism season (0.9 ± 1.12 items/ m^2) (MW, $p \leq 0.05$; Fig. 3B). For the protection status, no-take areas overall had a higher concentration of marine litter (3.6 ± 3.7 items/m^2) than public access areas (1.9 ± 0.54 items/m^2), although no significant differences were identified (MW, $p > 0.05$; Fig. 3C). In terms of beach orientation, south-west facing beaches had higher concentrations (4.6 ± 3.8 items/m^2) than north and west facing beaches although no significant differences were found (KW, $p > 0.05$; Fig. 3D). Of these beach orientations, the north facing beaches had the lowest concentrations of items (1.08 ± 0.61 items/m^2). In regards to material type, at all of the beaches the least common items by material type were unidentified and/ or chemicals (0.01 ± NA items/m^2), and the most common type were artificial polymer materials (2.8 ± 2.8 items/m^2) and a high variability was identified between material types (KW, $p < 0.001$; Fig. 3E). Finally, beaches mainly comprised of cobbles and seagrass had the highest abundances with an average of 7.5 items/m^2 and cobble beaches had the lowest concentration of items of 1.1 ± 0.6 items/m^2 (KW, $p > 0.05$; Fig. 3F).

3.1.2. Macro-litter data analyses

For the abundance GLM model, the best model included the following contributing factors: size class, material type, and tourism season. Regarding size classes, twice as many items were found in size classes A and B, which were significantly different from C and D (Table 4 and Fig. 4A; GLM, $p < 0.001$). In terms of the beach composition, beaches with cobbles and seagrass were significantly different than the other three beach types with almost twofold as much ML (Table 4 and Fig. 4B; GLM, $p < 0.001$). Finally, results from this analyses demonstrate that twice as many items are expected during low tourism season compared to the high tourism season (Table 4 and Fig. 4C; GLM, $p < 0.001$).

Table 2
Summary of the items collected for the macro-litter surveys for each beach and season by abundance (items/m^2), weight (g/m^2) and clean coastal index (CCI).

Beach	Tourism season	Abundance (items/m^2)	Weight (g/m^2)	CCI (numeric)	Coast Index
Sa Platgeta	Summer/ high	0.39	1	7.84	Moderate
Es Caló de ses Güies	Summer/ high	2.89	2.88	57.77	Very dirty
S'Espalmador	Summer/ high	0.28	1.19	5.53	Moderate
Cala en Ganduf	Summer/ high	0.41	18	8.13	Dirty
Es Caló des Forn	Summer/ high	0.3	1.17	5.94	Moderate
Sa Platgeta	Autumn/ low	1.25	1.87	24.97	Very dirty
Es Caló de ses Güies	Autumn/ low	4.67	5.15	93.44	Very dirty
S'Espalmador	Autumn/ low	1.20	1.52	24.06	Very dirty
Sa Platgeta des Pagès	Autumn/ low	5.84	8.34	116.76	Very dirty

3.2. Sediment samples

3.2.1. Abundance of micro-litter items

A total of 28 beach sediment samples were collected from the beaches of Cabrera MPA ranging from 4 to 9 samples depending on the size area of the beaches. Overall, an average of 13,418.9 ± 28,787.9 items/ m^2 weighing an average of 4428.8 ± 5133.1 g/m^2 and an average of 3125.3 ± 8373.0 items/kg d.w. (dry weight) were quantified. The beach with the highest abundance of ML was Es Caló de ses Güies (inside the port area) with an average of 48,642.0 ± 47,093.5 (1808.0–10,2624.0) items/m^2 (Fig. 5). The lowest abundance of ML was found in S'Espalmador (inside the port area) with 568.0 ± 174.5 (352.0–752.0) items/ m^2 (average ± standard deviation (minimum–maximum)) and the weight of the items collected at this location was one of the highest with 7612.9 ± 6153.8 (461–13,609.1) g/m^2. Significant differences were identified between beaches in regards to number of items/m^2, weight in g/m^2 and number of items/kg d.w. (Fig. 5). Within the port area, Es Caló de ses Güies was almost always different compared to the other two beaches, exhibiting a higher accumulation of ML (KW, $p < 0.05$) while, despite a high variability between the two beaches in the bay of Santa Maria, these were more similar compared to the beaches within the port

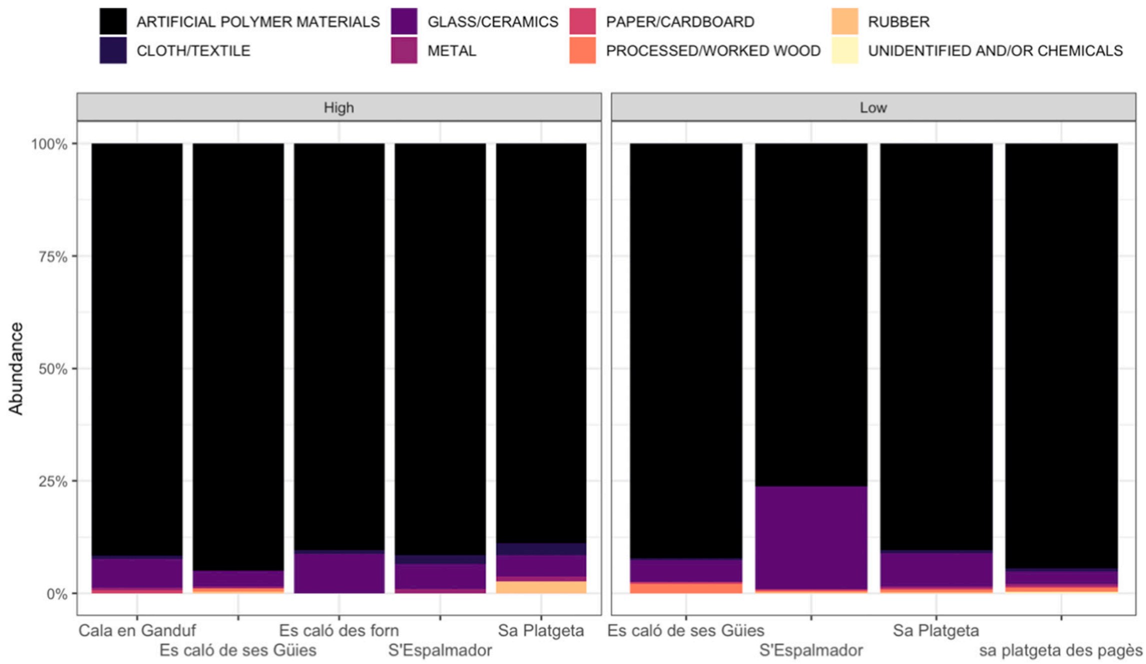

Fig. 2. Summary of macro-litter collected at each sampled beach during high and low tourism season. Stacked barplots indicate the percent (%) contribution of each of the items collected following the classification: artificial polymer materials, glass/ceramics, paper/cardboard, rubber, cloth/textile, metal, processed/worked wood and unidentified and/or chemicals. The beaches Cala en Ganduf and es Caló des Forn were found within the no-take area of Santa Maria while es Caló de ses Güies, s'Espalmador, sa Platgeta and sa Platgeta des Pagès were located within the Port of Cabrera.

area. In terms of the number of items/m^2, g/m^2 and items/kg d.w. of each of the sediment samples and their location on the beaches, the nonparametric Kruskal-Wallis test indicated that no significant differences were found between the shoreline, mid-shore and backshore transects (KW, $p > 0.05$) according to ML abundance.

3.2.2. *Characterization of micro-litter items*

Overall, for the abundance of micro-litter items in different size classes, 74.9% of the identified items were found in the 1–2 mm fraction, while 21.9% of the items were found in the 2–5 mm fraction. Note that only 3.2% of the items were >5 mm. A similar picture was found on each of the beaches (Fig. 6A) with two beaches accounting for less than 10% of the items in the sieve size fraction <5 mm: S'Espalmador found within the port area and Cala en Ganduf found within the restricted area.

According to colours of the items in the beach sediment, the most common colours were white/transparent (51.1%) and white/opaque (24.2%). Combined colours of black and blue comprised approximately 15% of the items and fewer than 10% of the items were red, green, multicolour or other. Regarding beaches, a similar pattern was observed at all of the beaches where ~50% of the items were white/transparent and a ~25% of the items were white/opaque while the remaining combination of colours were less than 25% of the total items with black and blue colours being the most abundant (Fig. 6B).

By shape, the most common typologies were fragments accounting for 79.8% of all items and the second most common were pellets (7.9%). The least common items were filaments, foam, microbeads and other which combined were less than 5% of all items collected. By beach, fragments were the most common, ranging from 56.6% in S'Espalmador to 82.6% in Es Caló des Forn (Fig. 6C). Pellets were the second most common at the majority of the beaches except for Cala Ganduf and S'Espalmador where films (7.5%; 11.6%) and foams (7.9%, 8.5%) were the second most common identified shapes. The beach with the highest concentration of pellets was located in the restricted area of Es Caló des Forn within the bay of Santa Maria (14.1%).

For polymer characterization, a total of 313 items were analysed using FTIR-ATR, corresponding to items quantified in beach sediment samples from a randomly sampled subset. The most common items found were high density polyethylene (HDPE) (44.1%) and low density polyethylene (LDPE) (19.5%), followed by polypropylene (17.2%) and polystyrene (6.2%) (Fig. 6D). There were several polymers with an abundance of <1% (ABR, ABS, CA, PES). Overall, HDPE was the most abundant at all beaches except for the beach of S'Espalmador where LDPE was the most abundant (38.1%). Polypropylene ranged from 10.1% in Cala Ganduf to 24.6% in Es Caló de ses Güies. Other materials that were common on specific beaches included polystyrene (14.0%) in Cala en Ganduf and paint derivatives (10%) in S'Espalmador.

3.2.3. *Micro-litter data analyses*

A non-metric Multi-Dimension Scaling (nMDS) was performed on the Bray-Curtis distance matrix for each of the plastic characteristics identified in the sediment samples (size, shape, colour and polymer characterization) by location considering the abundance of plastics (items/kg d.w.) from each plot. Significant differences in the size of the items were observed between beaches as the stress value was 0.01, indicating that differences between beaches and size classes were observed (ANOSIM, $R = 0.28$, $p < 0.01$) (Fig. 7A). Furthermore, significant differences in the shape of the items were observed between the beaches, as the stress value was 0.162 indicating that there were dissimilarities between the beaches and the type of litter items (ANOSIM, $R = 0.27$, $p < 0.01$) (Fig. 7B). Similar results were found for the colour with an overall stress value of 0.06 and significant differences were identified between locations (ANOSIM, $R = 0.27$, $p < 0.01$) (Fig. 7C). For the FTIR, the overall mean rank was $R = 0.14$, and no dissimilarities were found between the polymer characteristics of items found at the different beaches (ANOSIM, $R = -0.17$, $p > 0.05$) (Fig. 7D).

4. Discussion

This study covers macro- and micro-litter abundances on beaches from surveys in Cabrera MPA in the Balearic Islands. Macro-litter densities ranged from 0.3–5.8 items/m^2. Artificial polymers (plastics) were the most abundant macro-litter type accounting for over 90% of the

Table 3
Summary of the top ten items based on the marine litter classification and the number of items and the percent contribution: A) overall top ten items at all beaches; B) top ten items during the high tourism season in summertime; C) top ten items during the low tourism season in autumn.

	Category level 1	Code-items name	Number of items	Percent
A. Top ten overall				
1	Artificial polymers	G79-plastic pieces 2.5 cm >< 50 cm	1005	24.60%
2	Artificial polymers	G21-plastic caps/lids from drinks	373	9.13%
3	Artificial polymers	G95-cotton bud sticks	292	7.15%
4	Artificial polymers	G10-food containers incl. fast food containers	273	6.68%
5	Glass and Ceramics	G208-glass or ceramic fragments >2.5 cm	267	6.53%
6	Artificial polymers	G53-nets and pieces of net < 50 cm	220	5.38%
7	Artificial polymers	G4-small plastic bags, e.g. freezer bags, including pieces	101	2.47%
8	Artificial polymers	G67-sheets, industrial packaging, plastic sheeting	89	2.18%
9	Artificial polymers	G73-foam sponge	89	2.18%
10	Artificial polymers	G124-other plastic/polystyrene items (identifiable)	85	2.08%
B. Top ten high season				
1	Artificial polymers	G79-plastic pieces 2.5 cm >< 50 cm	276	32.82%
2	Artificial polymers	G4-small plastic bags, e.g. freezer bags, including pieces	71	8.44%
3	Artificial polymers	G53-nets and pieces of net < 50 cm	50	5.95%
4	Artificial polymers	G21-plastic caps/lids from drinks	42	4.99%
5	Artificial polymers	G59-fishing line/monofilament (angling)	42	4.99%
6	Artificial polymers	G95-cotton bud sticks	42	4.99%
7	Artificial polymers	G56-tangled nets/cord	41	4.88%
8	Glass and ceramics	G208-Glass or ceramic fragments >2.5 cm	35	4.16%
9	Artificial polymers	G73-foam sponge	30	3.57%
10	Artificial polymers	G23-plastic caps/lids unidentified	28	3.33%
C. Top ten low season				
1	Artificial polymers	G79-plastic pieces 2.5 cm >< 50 cm	729	25.84%
2	Artificial polymers	G21-plastic caps/lids from drinks	331	11.73%
3	Artificial polymers	G10-food containers incl. fast food containers	270	9.57%
4	Artificial polymers	G95-cotton bud sticks	250	8.86%
5	Glass and ceramics	G208-glass or ceramic fragments >2.5 cm	232	8.82%
6	Artificial polymers	G53-nets and pieces of net < 50 cm	170	6.03%
7	Artificial polymers	G58-fish boxes - expanded polystyrene	77	2.73%
8	Artificial polymers	G31-lolly sticks	70	2.48%
9	Artificial polymers	G67-sheets, industrial packaging, plastic sheeting	66	2.34%
10	Artificial polymers	G124-other plastic/polystyrene items (identifiable)	61	2.16%

quantified litter. These results are in agreement with previous studies for the Mediterranean Sea (Portman and Brennan, 2017; Vlachogianni et al., 2018). The majority of the macro-litter items collected were heavily degraded and difficult to identify the manufacturer; however, by identifying the type of items this gave us key information into the type of ML most abundant accumulating on the shoreline. The most common items found on the beaches of Cabrera MPA were similar to other regions such as the Adriatic and Ionian seas where G79-Plastic pieces 2.5 cm >< 50 cm were the most common litter category identified (~20%) in addition to cotton bud sticks, fishing material, single use plastic items (for example plastic straws) (Fig. 8A–D) (Vlachogianni et al., 2018). Glass/ceramics were the second most common items and this may be due to their heavier weight and negative buoyancy. Asensio-Montesinos et al., 2021 in the south-east of Spain found that smaller items embed within cobbles may remain buried for longer periods of time compared to larger items. It is important to highlight that one common item that was absent from the beaches in Cabrera MPA were cigarette butts and filters which are often one of the most common items found on beaches (Martinez-Ribes et al., 2007; Vlachogianni et al., 2018). This absence of butts and filters is largely due to the prohibition of smoking along Cabrera MPA, highlighting the success of implementing such measures. In Martinez-Ribes et al. (2007), cigarette butts and filters were the most common items found along all of the beaches surveyed in the Balearic Islands, highlighting the importance of implementing measures such as prohibiting smoking on public beaches. However, the results of the polymer characterization indicate that cellulose acetate was <1% of the characterized items and is commonly associated with cigarette filters (Andrady, 2015), indicating that remnants can be found on beaches potentially transported by sea from other regions (Lavers and Bond, 2017), or old remnants before measures were implemented in this MPA.

The results from the size classification indicated that smaller items were two-fold as frequent than larger items in all beaches during both low and high tourism season. This pattern is common across most beach surveys as small pieces, such as cotton buds and plastic drink bottles, are amongst the most frequent items. Furthermore, those beaches frequented during the high tourist season had significantly less ML compared to the beaches sampled during the low tourist season in the autumn. The was further confirmed by the CCI, which indicated that during the summer season all of the beaches with public access were moderately clean or dirty compared to beaches that were either closed to public access or during low tourism season. This relationship between tourism was not found by Vlachogianni et al. (2018) in the Ionian and Adriatic seas while Laglbauer et al., 2014 highlights that in Slovenia the geographic distribution of the beaches seem to be more correlated with plastic abundance than public affluence.

Cobble beaches with high accumulation of seagrass leaves on the shoreline contained more marine litter items than the other beach types. The accumulation of seagrass debris on the shoreline is an indication of the coastal marine seagrass habitats near the beaches and it is important to highlight seagrass habitats have been found to retain microplastic items, acting as a sink. Unsworth et al., 2021 identified an average of 215 ± 163 MPs/kg d.w. of sediment in seagrass meadows in the UK. While, Dahl et al. (2021) found a dramatic increase in microplastic pollution in seagrass soils from the mid-1970s. Similar results were also observed when considering egagropiles, spheroids formed by leaves shed by Mediterranean seagrass *Posidonia oceanica*. For example, items intertwined within the egagropiles were found in >50% of the samples (Pietrelli et al., 2017) while Sanchez-Vidal et al. (2021) found 17% of egagropiles contained plastic items with up to 1.470 plastic items/kg of dead seagrass. Sanchez-Vidal et al. (2021) also highlighted quadrants of surveyed beaches contained loose leaves of seagrass and found that over 50% of the samples contained plastic with up to 613 plastic items/kg of dead leaves, indicating they are possibly trapping these items. When considering beach composition, Orr et al. (2005) found cobble beaches to have the highest loading of wracks compared to gravel or sand beaches and moderate wave exposure increased deposition, which is in

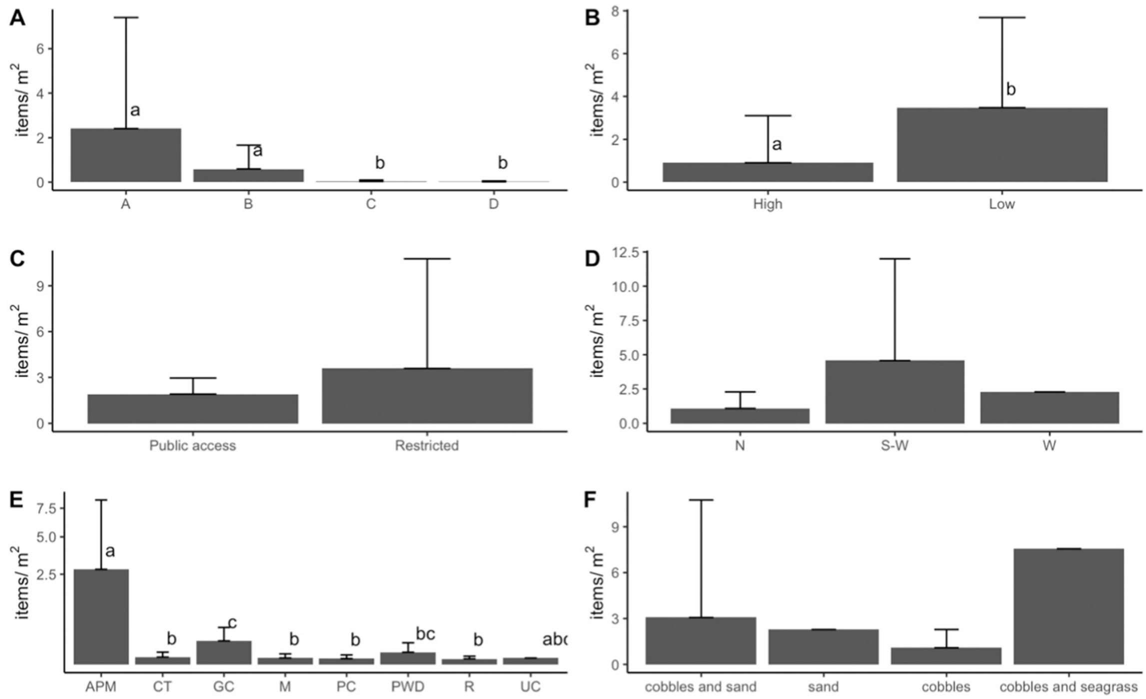

Fig. 3. Barplots of macro-marine litter (items/m^2) collected during the beach surveys in Cabrera by: A) marine litter size class: A (<25 cm^2), B (<100 cm^2), C (<400 cm^2), and D (<2500 cm^2), B) beach tourism pressure (high and low), C) beach protection status (beach of public access and restricted beach), D) beach orientation, E) marine litter material collected: APM (artificial polymer materials), GC (glass and ceramic), M (metal), CT (cloth and textile), PWD (processed and worked wood), PC (paper and cardboard), R (rubber), UC (unidentified and/or chemicals) (y-axis square-root transformed), and F) beach morphology (cobbles and sand, sand, cobbles, and cobbles and seagrass). Error bars indicate a 95% confidence interval and significant differences are indicated by different letters.

Table 4
Summary of the results from the generalized linear model for size class, beach composition and tourism season according to macro-litter items found at all beaches.

Coefficients:	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	−2.3136	0.1779	−13.007	<2e-16	***
B	−0.2684	0.2157	−1.244	0.213369	
C	−1.8124	0.3355	−5.402	6.60E-08	***
D	−2.3185	0.4975	−4.66	3.16E-06	***
Sand	−0.4553	0.2431	−1.872	0.061145	.
Cobbles	−0.4293	0.2391	−1.796	0.07255	.
Cobbles and seagrass	0.8561	0.2531	3.383	0.000718	***
High tourism	−0.9969	0.1942	−5.135	2.83E-07	***

agreement with this study.

For the micro-litter items in beach sediment, densities ranged from 568.0 ± 174.5 to 48,642.0 ± 47,093.5 items/m^2 and the dominant plastic type was polyethylene (both HDPE and LPDE) regardless of the location. Small items from the size class 1–2 mm were the most abundant MPs identified in the study area. Regarding colours, white and transparent were the most common colours, their abundance may be attributed to items that have been degraded from larger items. Interestingly, transparent fragments were absent from shallow coastal sediment samples collected within Cabrera MPA (Alomar et al., 2016). The most common items were fragments although some areas had extremely high concentrations of pellets (Fig. 7E–F). Considering that no industrial pellets factories are located in the Balearic Islands, this occurrence provides evidence of hydrodynamic transfer from other regions of the Mediterranean Sea.

When considering the polymer types, the most common are all positively buoyant polymers such as HDPE, LDPE, PP, and PS (Andrady, 2011) and results from this study are in agreement with items from beach sediments in other regions of the Mediterranean Sea (Vianello et al., 2013). Interestingly, items that were less dense than that of sea

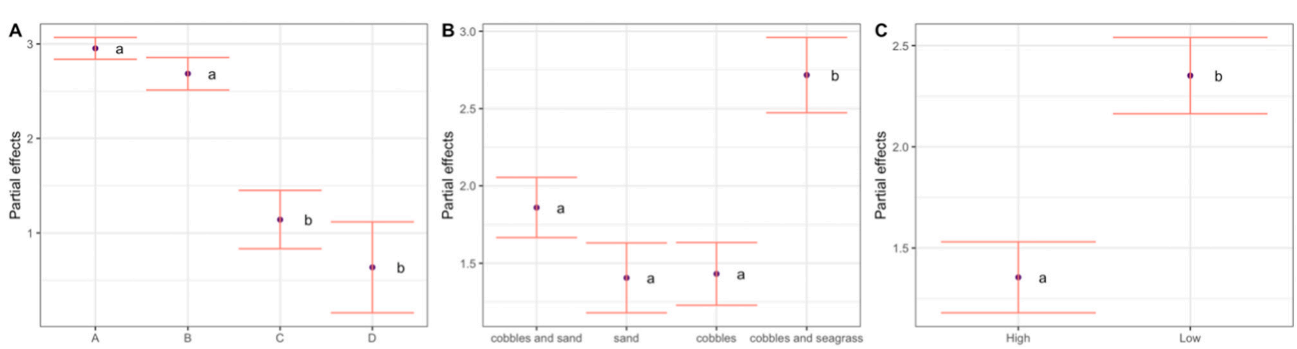

Fig. 4. Partial effects for the generalized linear model for the distribution of macro-litter items collected. Significant fixed factors were: A) size class, A (<25 cm^2), B (<100 cm^2), C (<400 cm^2), and D (<2500 cm^2), B) predominant beach type and C) tourism season. Error bars indicate a 95% confidence interval and significant differences are indicated by different letters.

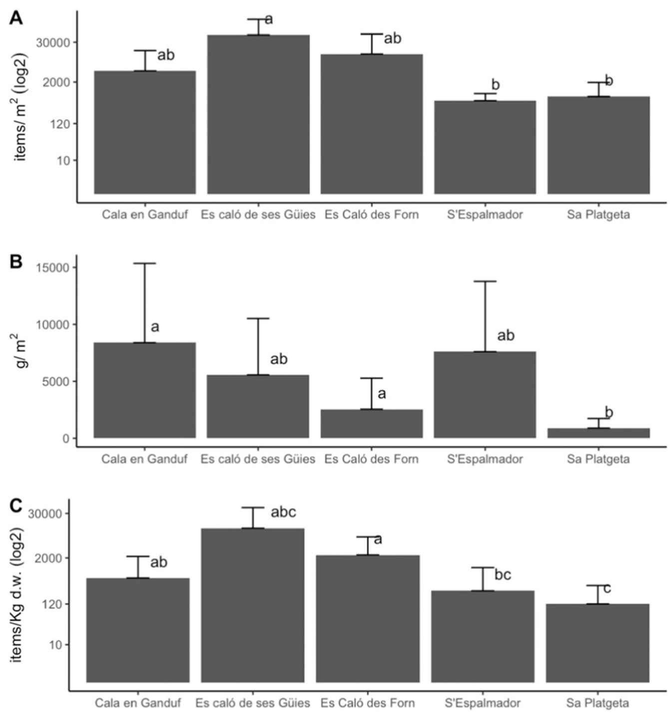

Fig. 5. Barplot summary of abundance (items/m^2; y-axis Log2 transformed), weight per (g/m^2) and items per kg (items/kg dw; y-axis Log2 transformed) of microparticles identified in beach sediment samples at each location. Significant differences are indicated by different letters and error bars indicate 95% confidence intervals.

water such as polyvinyl chloride (PVC) and polyethylene terephthalate (PET) were absent from the beach samples, probably indicating that these items most likely might have settled on the seafloor which indicates the need to analyse seafloor sediments in this region in future studies. A study from Dahl et al. (2021) for seafloor sediments in *P. oceanica* meadows within Cabrera MPA identified polymers such as polyethene and plasticizers used almost exclusively in 19 products made up of PVA. Further research into the deposition of polymers is needed to better understand their fate in each compartment.

Previous studies on ML have highlighted the recreational use of beaches as a main source of marine litter across beaches in the Mediterranean Sea (Grelaud and Ziveri, 2020); however, in Cabrera MPA a different scenario was evident as higher amounts of ML were quantified during the autumn season, which receives far fewer visitors than the summer season. Although several studies have highlighted the main source of ML comes from terrestrial sources, numerical models from Liubartseva et al., 2019 identify shipping as a principal source of ML contributing to 55–88% of all plastic items found along MPA shorelines. During the high tourism season, beaches were relatively cleaner than during the autumn season, when tourism is substantially declining. Firstly, beaches within the port area are actively cleaned daily during high tourism while these maintenance decreases with the decline of visitors. Additionally, awareness measures regarding marine litter are provided to all guests when arrival to the island by guides during the high tourism season while year-round there are billboards with marine litter indications to visitors who visit the island during low season. Grelaud and Ziveri, 2020 exemplified the positive impact that awareness campaigns have on beaches heavily frequented by tourists, especially in the Balearic Islands. In general, a considerable amount of debris was found during months when designated clean-ups are less frequent with fewer tourists.

Overall the abundance of micro-litter items on beaches in Cabrera

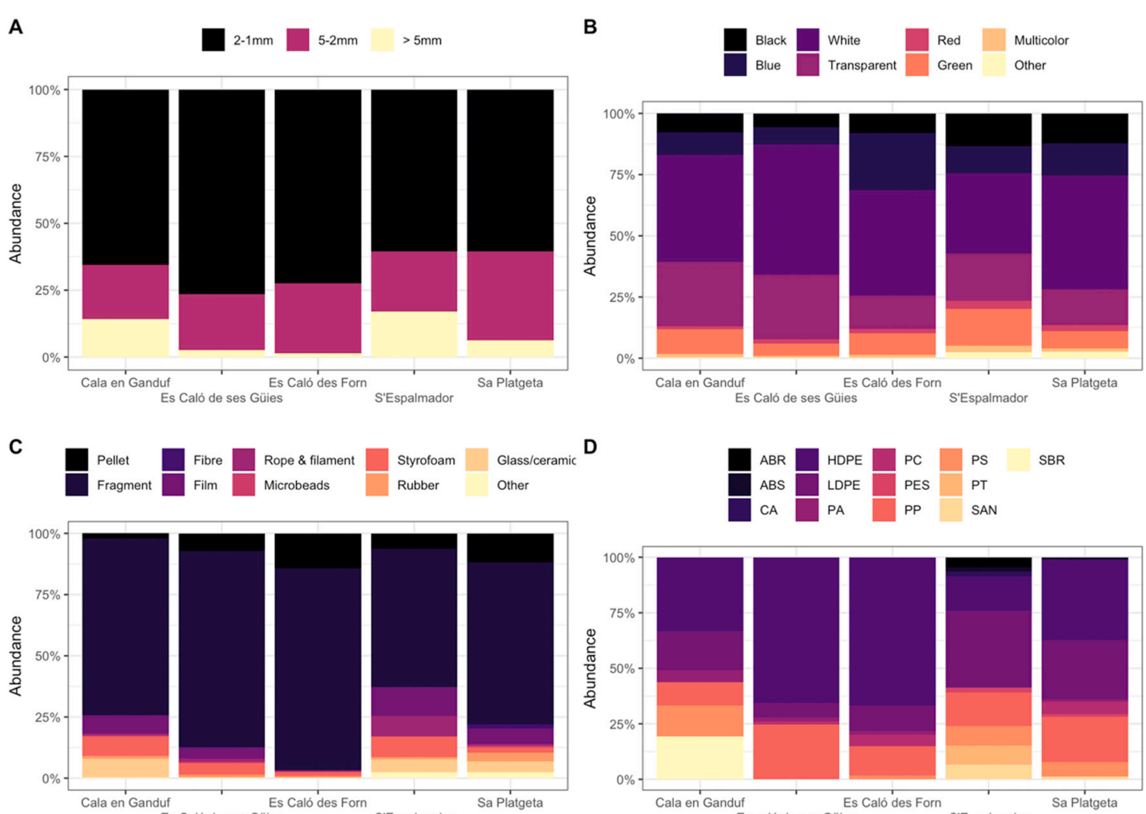

Fig. 6. Summary of the contribution of micro-litter plastic items in the sediment samples at each beach: A) size, B) colour, C) type and D) polymer: high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyamide (PA), polyester (PES), polypropylene (PP), polystyrene (PS), acrylonitrile-butadiene rubber (ABR), acrylonitrile butadiene styrene (ABS), styrene – acrylonitrile (SAN), styrene - butadiene rubber (SBR), and paint (PT).

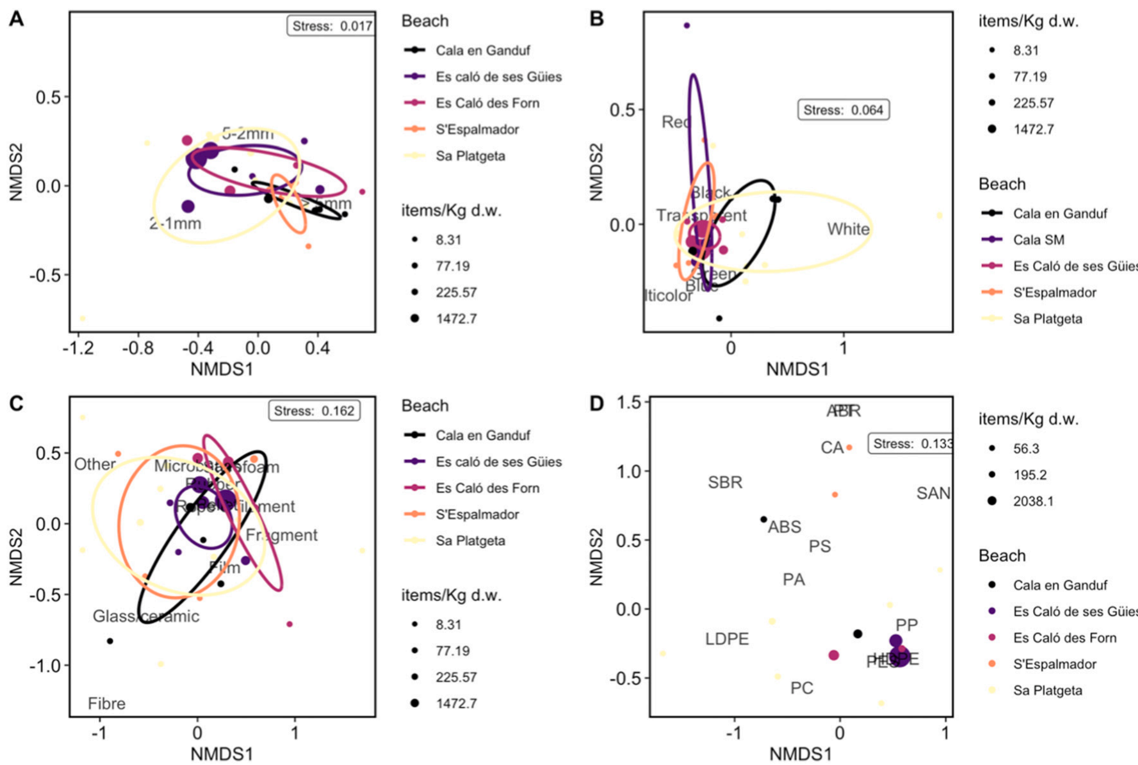

Fig. 7. Visualization of the results from the nMDS for determining the similarity between the physical characteristics of the micro-litter items collected from the sediment samples from each location: A) size, B) colour, C) type and D) polymer. Bubble size represents items/kg d.w. sediment from each of the sampled sediment plots.

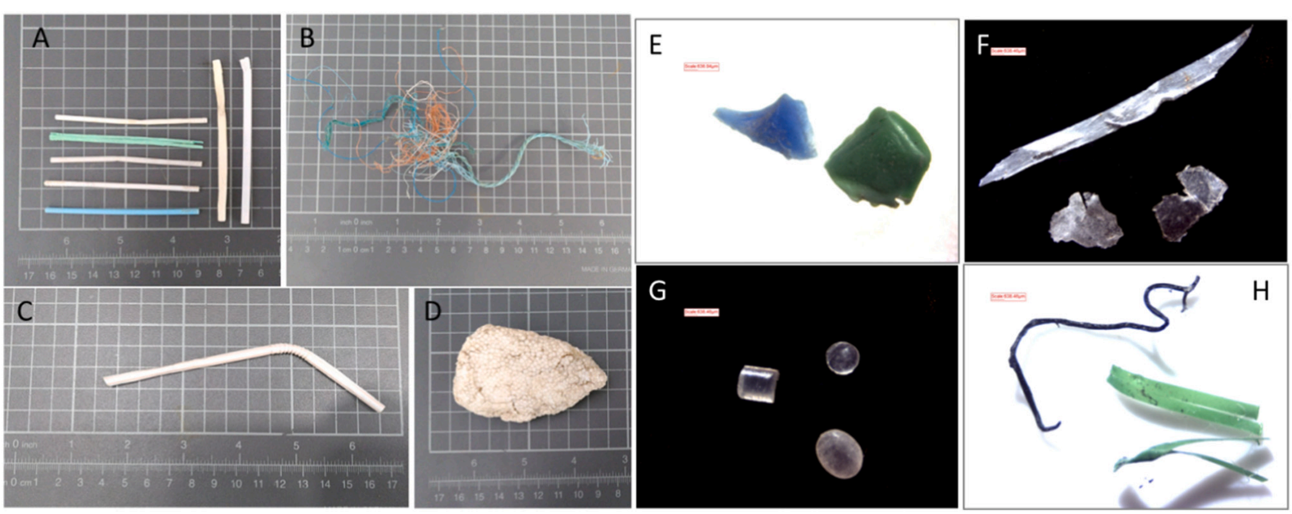

Fig. 8. Examples of all identified items from the marine litter beach surveys A) earbud sticks, B) fishing line/net, C) straw, and D) piece of foam and the microplastic types within beach sediments: E) fragments, F) films, G) pellets and H) filament.

MPA ranged from 568.0 ± 174.5382 items/m^2 to 48,642.0 ± 47,093.5 items/m^2 which is very high in comparison to beach sediments from other regions (specifically MPAs in the Mediterranean region) (Table 5). These results were more similar to the concentrations found on remote Henderson island where up to 671.6 items/m^2 were found on the beach with up to 4496.9 pieces/m^2 within the first 10 cm (Lavers and Bond, 2017). These authors highlight that remote areas are becoming reservoirs for plastic waste lost in the marine environment and considering these areas often preserve endemic and vulnerable species, the risk of negative impacts for these species is even more concerning. Compa et al. (2019a) and Soto-Navarro et al. (2021) emphasize that Mediterranean habitats, especially MPAs and coastal areas, are at risk of plastic debris, drawing further concerns about the increased number of items found in this study that accumulate in beach sediments within Cabrera MPA.

The analysis of the physical characteristics of the microplastics items across all beaches indicates dissimilarities for size, shape and colour. There could be several reasons for this; first of all, the differences between size classes are an indication of weather degradation from UV radiation of items collected on beaches resulting in the embrittlement of plastics items breaking down into smaller items (Andrady, 2015). Consequently, the heterogeneity of the physical characteristics observed in the items could be an indication of the in situ weathering of larger

Table 5
Comparison of macro and micro-plastic debris studies for beaches from the Mediterranean and Black Sea. Summary of the results from each study for the region, number of surveys carried out, average ± standard deviation of ML (minimum and maximum), units (e.g. items/m^2, items/kg) and study.

Beach plastic size	Region	Year	N	Location	Average ± SD	Units	Average ± SD	Units	References
Macroplastic	Balearic Islands	2019	9	Beach	1.9 ± 2.4 (0.3, 5.8)	items/m^2	4.6 ± 6.9 (1.0, 18.0) (minimum, maximum)	g/m^2	This study
Macroplastic	Adriatic-Ionian macroregion	2014–2016	31	Beach	0.08–11	items/m^2	–	–	Vlachogianni et al., 2018
Macroplastic	Jisr (Israel)	2016	21	Beach	5.1	–	–	–	Portman and Brennan, 2017
Macroplastic	Slovenian coast	2012	6	Beach	1.25	–	4.45	–	Laglbauer et al., 2014
Macroplastic	Balearic Islands	2005	32	Beach	36	items m^{-1}	32 ± 25	g m^{-1}	Martinez-Ribes et al., 2007
Microplastic	Balearic Islands	2019	28	Beach	13,523.7 ± 20,302.3	items/m^2	3125.25 ± 8372.996	items kg^{-1}	This study
Microplastic	Algeria	2017	110	Beach	7.6 ± 18.8–66 ± 107.28	items/m^2	–	–	Taïbi et al., 2021
Microplastic	Baltic	2015		Beach	–	–	160 ± 86	items kg^{-1}	Urban-Malinga et al., 2020
Microplastic	Tunisian coast	2017	48	Beach	254 ± 141–1100 ± 1629 (minimum–maximum)	items/m^2	56 ± 61–182 ± 233 (minimum–maximum)	items kg^{-1}	Constant et al., 2019
Microplastic	Ionian		34	Beach	17 to 95	items/m^2	–	–	Digka et al., 2018
Microplastic	Tunisian coast	2017		Beach	–	–	141.20 ± 25.98–461.25 ± 29.74 (minimum - maximum)	items kg^{-1}	Abidli et al., 2018
Microplastic	Slovenian coast	2012	18	Infralittoral	–	–	155.6	items kg^{-1}	Laglbauer et al., 2014
Microplastic	Slovenian coast	2012	18	Beach	–	–	133.3	items kg^{-1}	Laglbauer et al., 2014

items. Fok et al., 2017 identified continued fragmentation of strand plastic items of beaches based on their size distribution. In this study, polystyrene was abundant on the pristine beach of Cala Ganduf, which could be attributed to the breakdown of styrofoam boxes or fishing buoys stranded on the shoreline (Lee et al., 2014; Martinez-Ribes et al., 2007). These results highlight the importance of beach maintenance measures to avoid the degradation and fragmentation of items that accumulate on beaches for long periods of time.

Few of the items collected could be attributed to items derived from the visitors or recreational boats, indicating that most of the ML items were most likely transferred to Cabrera MPA via hydrodynamic processes. Although nearshore transport models for Cabrera MPA are currently unavailable, backtracking models of currents at a local level using nearshore microplastic observations in the Balearic Islands highlight the connectivity between the islands of this archipelago and the countries bordering the western Mediterranean Sea (Compa et al., 2020). Liubartseva et al. (2019) identified plastic retention fluxes of MPAs within the Balearic Islands indicating that plastics are not only accumulating on the shoreline but are also being brought back to sea (Fok et al., 2017; Zhang, 2017). In addition to the potential transportation of ML via currents, there are spatial and seasonal differences in wave exposure dependent on the region in Cabrera MPA that might affect spatial and temporal distribution of ML. For example, many of the locations in this study are situated in sheltered areas with an apparent low wave exposure index, a combination of wind direction and intensity, during the summer and fall seasons, while higher exposure is found on the eastern coast in the summer and high wave exposure in the autumn on the western coast (Alvarez et al., 2010). A localized numerical model highlighted the residence time of particles within the port area of Cabrera MPA to range between 1 h to over 30 days (Orfila et al., 2005), indicating the complexity and variability of capturing nearshore circulation patterns. Furthermore, although this goes beyond the purpose of this study, it is important to highlight the complexity of cross-shore particle transport; Forsberg et al. (2020) found that both wind and waves in addition to the properties of plastics, modulate the behaviour of plastics in these areas. Forsberg et al., 2020 highlights larger and heavier items behave like sand and accumulate in the foreshore where the wave breaks. Future studies into the wave and wind regimens in the study area are needed to identify the general accumulation of ML on the shoreline.

Results from this study highlight that beaches in MPAs are becoming reservoirs for marine litter. Despite the protected status of Cabrera MPA, plastic pollution (macro- and micro-litter) was abundant throughout the MPA. Several mitigation measures may help minimize its accumulation on the shoreline such as regularly scheduled maintenance activities year-round to mitigate the accumulation of ML throughout the region and periodic clean-ups of beaches, even during the off season, which can be an effective action to prevent accumulation and the reduction of the fragmentation of larger items to smaller ones. Moreover, visitor awareness measures to reduce direct loss of marine litter from visitors (either by land or sea) of the most common items found within the port area, especially considering the success of already measures in use such as prohibiting smoking. Additionally, further research into beach dynamics and fluxes of ML on coastal shorelines joint to a better understanding of the delivery currents and local wave and wind patterns are needed to identify more effective mitigation measures and minimize the possibility of beaches being both a sink for ML and a source for microplastics. The baseline data collected for the Cabrera MPA in this research provides crucial data for managers for this region and others within the Balearic Islands to develop reduction and mitigation measures to preserve coastal ecosystems from marine pollution.

CRediT authorship contribution statement

MC: Writing original draft, Methodology, Investigation, Formal analysis, Visualization. CA: Formal analysis, Investigation, Writing, Reviewing & Editing, Project administration. MM: Methodology, Validation, Resources, Writing, Reviewing & Editing. EA: Methodology, Investigation, Writing, Reviewing & Editing. SD: Validation, Investigation, Resources, Writing, Reviewing & Editing, Supervision, Project administration, Funding acquisition.

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.

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