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The seafloor under study: analysis of substrate and habitat influence on the distribution of benthic litter☆

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ABSTRACT

The oceans are among the most polluted environments due to marine litter, primarily driven by anthropogenic impacts and oceanographic conditions. Once in the environment, marine litter can sink through the water column and accumulate along the seafloor. The density of macrolitter along the continental shelf of the Spanish western Mediterranean Sea has been systematically quantified annually from 2015 to 2022 during bottom trawl scientific surveys. The present study explores spatial and temporal patterns of marine litter on the seafloor, considering substrate and habitat features as key factors potentially influencing its accumulation. A mean value (±SD) of 19.26 ± 138.63 kg/km^2 of macrolitter was quantified. 'Plastics' and 'fishing gears' were the two main categories quantified with mean values of 4.46 ± 39.80, and 5.01 ± 124.08 kg/km^2, and were present in 87 % and 50 % of the hauls, respectively. Statistically significant differences in total marine litter, 'plastic', and 'fishing gears' densities within subareas, years, substrata, and EUNIS19C habitat were identified. The 'rock or other hard substrata' and 'coarse & mixed sediment' substrata showed higher densities of marine litter than 'sand' substrata. Additionally, coarse and mixed sediments in upper and lower bathyal Mediterranean habitats ('ME35/MF35' and 'ME45/MF45') showed the highest marine litter densities, with significantly higher values compared to most other habitat types. These results indicate that coarse sediment habitats are the most affected by marine litter accumulation, highlighting the role of substrate type in retention processes and the increased potential vulnerability of the benthic species inhabiting these habitats.

1. Introduction

The seafloor, the largest assemblage of interconnected ecosystems by spatial extent, has its ecological functioning strongly mediated by benthic biodiversity (Woodin et al., 2016). In recent years, there has been a growing interest in understanding the distribution and composition of seafloor habitats, as evidenced by the revision of existing habitat classifications and the development of various tools to enhance resolution and classification (Liu et al., 2024; Montefalcone et al., 2021). In this sense, the seafloor is composed of different types of substrata, ranging from soft sediments to hard bottoms, each hosting distinct marine organisms. These organisms exhibit varying response and effect traits, which influence their functional roles and interactions with both the benthic habitat and, in many cases, the water column throughout different stages of their life cycle (Beauchard et al., 2023). Remotely operated vehicle (ROV) explorations of the Mediterranean deep sea have revealed that the seabed harbors a variety of habitats, including *Posidonia oceanica* meadows and rhodolith/maërl beds, which sustain high biodiversity and host habitat-forming species such as gorgonians or black corals, listed in the Red List of the International Union for Conservation of Nature (Romagnoli et al., 2021). The ecological condition of these ecosystems may play a key role in determining their capacity to resist and recover from disturbances (Rosenberg et al., 2002), and several pressures have impacted the seafloor during the last decades including, but not limited to: demersal trawling fishing; the increment of nutrients linked to episodes of hypoxia, or the extraction of seabed mineral resources among others (Foden et al., 2011; Korpinen et al., 2013). In addition to all these well-known pressures, the increased accumulation of marine litter on the seafloor must be considered as a pressure that can affect the general status of the environment and marine organisms.

The Marine Strategy Framework Directive (MSFD) aims to achieve Good Environmental Status (GES) in the EU's marine waters. To assess this status, 11 qualitative descriptors must be considered, describing the

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environment when GES is achieved being the descriptor 10 (D10) addressing marine litter. The MSFD has to be implemented in all marine waters of the 22 EU Member States, and Spain is the country with one of the most extensive marine areas under its jurisprudence, with 7,905 km of coastline, and approximately 2,491 km located on the Mediterranean coast; www.ine.es). In this sense, Spain developed five marine regions called demarcations, two of them located in the western Mediterranean Sea: the Levantine-Balear demarcation (LEBA), which includes the coast that extends from Cape Creus (located in the northeast of the Iberian Peninsula) to Cape Gata (located in the southeast of the Iberian Peninsula) as well as the Balearic Islands; and the Strait and Alboran demarcation (ESAL), which it is located in the westernmost part of the Mediterranean Sea, extending from Cape Spartel (North Africa) and passing through the Strait of Gibraltar to the Alboran Sea, including the waters surrounding the Spanish lands of the area such as the autonomous cities of Ceuta and Melilla. Together, both demarcations cover a total marine area of 259,011.03 km^2 within the Mediterranean Sea.

These two demarcations have different pressures that can generate an unequal distribution of marine litter. In terms of anthropogenic pressures, the LEBA demarcation hosts several important cities with relevant commercial ports (Barcelona, Valencia, or Palma de Mallorca), and important touristic and maritime traffic activity, overall generating cumulative anthropogenic pressures (Coll et al., 2012). In addition, the Northern Current flows along the continental Spanish slope, which has already been related to the distribution of marine litter (Ourmieres et al., 2018). Regarding the ESAL demarcation, an intense greenhouse cultivation activity exists (approximately 25,902 ha of crops in the 2005 season) along the western coast of Almería (Sanjuan Estrada, 2007), followed by Murcia and Granada, generating tonnes of plastic litter (Tolón Becerra and Lastra Bravo, 2010) which, due to its proximity to the marine environment and in case of absence of proper waste management, could potentially be released into the marine environment (Martínez-Campos et al., 2022). Additionally, the Strait of Gibraltar has one of the highest levels of marine traffic regarding open waters in the Mediterranean Sea (www.fleetmon.com) and, due to its oceanographic characteristics, the Alboran Sea has been considered a 'transit area' favorable for water exchanges between sub-basins, but not for litter accumulation (Mansui et al., 2015).

Given the importance of seafloor habitats and their growing exposure to marine litter, understanding the factors driving litter accumulation is essential. Marine litter is considered to be unevenly distributed across the seafloor, with its presence influenced by substrate type and habitat characteristics. In this context, the present study aims: i) to analyze the spatial distribution of marine litter in two Mediterranean Spanish demarcations (LEBA and ESAL) of the MSFD as well as the temporal trend in a 8 years period (2015–2022); ii) to classify into different categories the marine litter quantified along the western Mediterranean Spanish continental shelf and platform; and iii) to test if there are specific seafloor habitats more affected by marine litter pollution than others.

2. Material and methods

2.1. Study area

This study was performed along the western Spanish Mediterranean Sea, from the French border to the Strait of Gibraltar, as well as in the Balearic Sea (Fig. 1). Marine litter was collected during experimental bottom trawl surveys conducted from 2015 to 2022 as part of the ongoing International Bottom Trawl Survey from the Mediterranean program (MEDITS) (Bertrand et al., 2002) and on board of the Research Vessel (R/V) Miguel Oliver (70 m length and 12 m width). Surveys were carried out yearly from May to June. A stratified sampling scheme with five bathymetric strata was applied (A: 0–50, B: 51–100, C: 101–200, D: 201–500, E: 501–800 m). To consider the implementation of the MSFD in Spanish waters, the study area was divided into the two MSFD Mediterranean Spanish subareas: the LEBA and the ESAL demarcations. Additionally, the study area was also divided into the Food and Agriculture Organization of the United Nations (FAO) division: GSA 1 (Alboran Sea), GSA 2 (Alboran Island), GSA 6S (Valenciana), GSA 6N (Tramontana), and GSA 5 (Balearic Sea) (FAO, 2009; García-Rivera et al., 2018). Given that the border between both demarcations divides the GSA 1 into two parts, the present study considers separately the section of the GSA 1 from the LEBA demarcation to that one from the

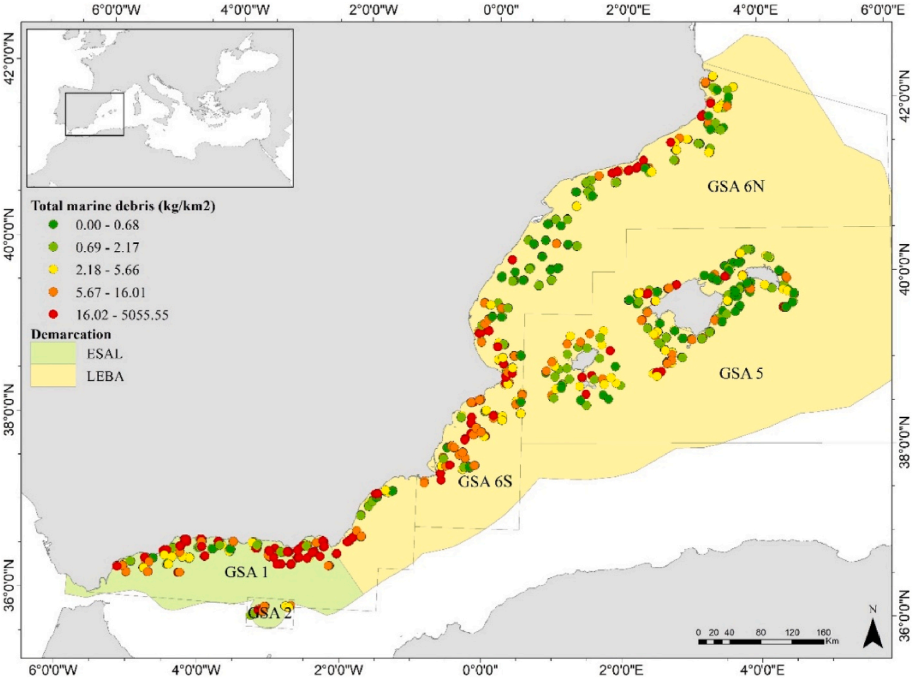

Fig. 1. Study area with demarcations and the Spanish GSAs boundaries defined. Densities (kg/km^2) of seafloor total marine litter collected during MEDITS surveys from 2015 to 2022. Classification has been made by using quintiles.

ESAL demarcation and this GSA is defined as ‘section GSA 1’ (Fig. 1). Additionally, due to the low number of hauls carried out in GSA 2 in the ESAL demarcation, all hauls carried out in this area were included jointly with those from GSA 1 being geographically comparable to ESAL demarcation (Fig. 1).

2.2. *Sampling gear and classification onboard*

All hauls were performed using the bottom trawl gear GOC 73, which was designed for experimental fishing with scientific purposes for the MEDITS program. The sampling gear has standard dimensions throughout all Mediterranean scientific surveys (width of 22 m, height of vertical opening 2 m, length of 40 m, stretched mesh size of a cod-end of 20 mm; Fiorentini et al. (1999)) and can be used to operate from depths of 10–800 m (Carpentieri, 2020). The trawling hauls had an approximate duration of 30 min along bottoms shallower than 200 m depth and 60 min along bottoms deeper than 200 m at a constant velocity of approximately 3 knots. Latitude and longitude, mean depth, trawl speed, and duration of the hauls were recorded. At each surveyed station, once aboard, all collected marine litter items were sorted into ten main categories according to the MEDITS protocols (plastic, fishing gears, pottery, textiles, glass, metal, paper, rubber, sanitary litter, and a last category of other materials, which includes all anthropogenic items that do not fall into the specific categories listed) and weighted to the nearest 0.1 g using a high-precision scale (MARELEC). Processed wood was not analyzed as a distinct category, given that during part of the study period, natural wood was subsumed under the same classification. Only densities of litter from valid hauls, defined as hauls conducted under standardized and acceptable conditions, ensuring reliable sampling in accordance with the survey protocol, were included in this study. Areas of the hauls were calculated considering the length of the haul and the gear width. The density (±SD) of marine litter in kilograms per area (kg/km^2) was calculated for each of the classified categories (Table 1). This standardization accounts for differences in trawling duration ensuring comparability across all hauls regardless of depth or sampling effort.

2.3. *Habitat characterization*

The European Marine Observation and Data Network (EMODnet) is a consortium of organizations supported by the EU’s integrated maritime policy. The Seabed Habitats section provides access to the seabed habitat dataset, including the EMODnet broad-scale seabed habitat map for Europe (EUSeaMap). In the present investigation, the substrate, and the European Union Nature Information System habitat classification reviewed in 2019 (EUNIS2019C) from the available EUSeaMap seafloor habitat classification have been considered (Table 2). According to the substrate into 6 types: coarse & mixed sediment, fine mud, muddy sand, rock or other hard substrata, sand, and sandy mud. Moreover, according to the EUNIS2019C habitat classification, which includes some specific Mediterranean biotopes and details of the deep-sea sections included in the previous habitat EUNIS classification (2007–2011) (Montefalcone et al., 2021), the area was classified into 15 habitats (Table 2; geodatabase available in https://emodnet.ec.europa.eu/geoviewer/). To calculate the density of seafloor litter in the substrata, and EUNIS19C habitats the ‘intersect’ analysis tool of ArcGIS (version 10.8) was used.

2.4. *Data analysis*

Several Kruskal-Wallis (KW) tests were conducted to assess differences in the density (kg/km^2) of total marine litter, ‘plastic’, and ‘fishing gear’. The analyses evaluated temporal variation through ‘survey year’, spatial differences via ‘GSA’, and ‘depth strata’, and habitat-related classification by considering ‘substrate’, and ‘EUNIS19C’. Where significant differences were found, Dunn’s post hoc tests were applied to identify specific group-level contrasts. To assess long-term monotonic

Table 1

Summary of the mean values (±SD) of the densities of each seafloor marine litter category according to the spatial (A) and temporal (B) distribution.

A. Spatial distribution													
Demarcation	GSA	n hauls	Plastic	Fishing gears	Pottery	Textiles	Glass	Paper	Metal	Sanitary debris	Rubber	Other	Total
ESAL	GSA 1 and 2	396	5.75 ± 14.19	4.34 ± 19.31	0.11 ± 1.76	1.21 ± 4.00	0.49 ± 1.69	0.01 ± 0.16	1.06 ± 5.98	0.00 ± 0.00	0.19 ± 1.97	6.73 ± 20.66	19.88 ± 37.14
Total ESAL		396	5.75 ± 14.19	4.34 ± 19.31	0.11 ± 1.76	1.21 ± 4.00	0.49 ± 1.69	0.01 ± 0.16	1.06 ± 5.98	0.00 ± 0.00	0.19 ± 1.97	6.73 ± 20.66	19.88 ± 37.14
LEBA	Section GSA 1	79	8.50 ± 22.39	0.81 ± 2.56	0.37 ± 3.33	2.65 ± 12.96	1.99 ± 5.50	0.02 ± 0.16	0.46 ± 1.64	0.00 ± 0.00	0.17 ± 1.46	25.61 ± 81.09	40.58 ± 93.83
	GSA 5	495	2.04 ± 5.59	2.11 ± 17.32	1.37 ± 15.87	0.48 ± 2.17	1.02 ± 3.83	0.00 ± 0.01	0.27 ± 2.28	0.01 ± 0.17	0.33 ± 2.77	1.19 ± 8.68	8.82 ± 28.70
	GSA 6N	437	6.62 ± 75.65	0.17 ± 0.82	0.10 ± 1.27	4.54 ± 63.33	0.31 ± 1.81	0.00 ± 0.07	0.31 ± 2.14	0.90 ± 13.30	0.02 ± 0.29	2.48 ± 7.70	15.45 ± 114.91
	GSA 6S	335	1.80 ± 2.78	16.30 ± 275.20	0.07 ± 0.63	1.26 ± 4.36	1.02 ± 3.32	0.02 ± 0.24	0.27 ± 1.68	0.03 ± 0.42	0.06 ± 0.40	8.96 ± 22.03	29.78 ± 276.75
Total LEBA		1,346	3.85 ± 43.68	4.94 ± 137.85	0.57 ± 9.68	2.12 ± 36.37	0.85 ± 3.34	0.01 ± 0.13	0.29 ± 2.06	0.31 ± 7.59	0.15 ± 1.74	4.98 ± 24.21	18.07 ± 155.77
B. Temporal distribution													
Survey year													
	2015	225	2.21 ± 6.88	0.64 ± 2.82	0.25 ± 3.60	1.37 ± 9.33	0.39 ± 21.84	0.00 ± 0.01	0.37 ± 3.12	0.00 ± 0.00	0.01 ± 0.10	3.45 ± 19.73	8.68 ± 25.18
	2016	224	2.97 ± 8.59	2.76 ± 20.73	1.76 ± 14.78	1.07 ± 3.24	1.82 ± 5.68	0.01 ± 0.10	0.97 ± 5.30	0.00 ± 0.00	0.05 ± 0.48	11.20 ± 49.82	22.61 ± 63.16
	2017	227	3.45 ± 8.18	1.31 ± 7.96	1.22 ± 17.97	1.30 ± 7.70	0.17 ± 0.75	0.00 ± 0.00	0.20 ± 1.87	0.03 ± 0.50	0.20 ± 2.29	1.75 ± 4.63	9.64 ± 26.97
	2018	217	4.20 ± 14.71	24.39 ± 341.69	0.19 ± 2.38	1.71 ± 5.96	0.59 ± 2.27	0.03 ± 0.25	0.25 ± 1.58	0.01 ± 0.04	0.23 ± 1.57	5.24 ± 18.75	36.85 ± 343.39
	2019	224	3.86 ± 8.62	2.98 ± 17.29	0.02 ± 0.18	1.14 ± 3.72	0.93 ± 3.21	0.01 ± 0.08	0.34 ± 2.04	0.02 ± 0.15	0.07 ± 0.80	7.25 ± 15.38	16.63 ± 27.79
	2020	106	20.43 ± 153.35	0.23 ± 0.78	0.00 ± 0.00	0.26 ± 1.09	0.63 ± 2.94	0.00 ± 0.00	0.07 ± 0.22	0.00 ± 0.00	0.10 ± 0.92	1.37 ± 4.76	23.09 ± 153.70
	2021	234	3.38 ± 13.78	1.72 ± 13.71	0.02 ± 0.30	6.42 ± 86.20	0.63 ± 1.96	0.00 ± 0.00	0.63 ± 3.63	1.28 ± 17.28	0.09 ± 0.71	5.93 ± 20.11	20.11 ± 120.26
	2022	285	2.86 ± 11.80	3.19 ± 19.88	0.12 ± 1.47	1.18 ± 4.45	0.87 ± 2.94	0.02 ± 0.24	0.64 ± 4.65	0.34 ± 5.12	0.43 ± 3.48	4.86 ± 15.87	14.51 ± 35.37
C. Mean values of the whole study area		1,742	4.28 ± 38.98	4.80 ± 121.48	0.47 ± 8.55	1.92 ± 32.01	0.77 ± 3.05	0.01 ± 0.14	0.47 ± 3.39	0.24 ± 6.67	0.16 ± 1.79	5.38 ± 23.45	18.49 ± 138.02

trends in the data, a non-parametric Mann-Kendall test was applied in conjunction with the Theil-Sen slope estimator, which computes the median of all pairwise slopes within the time series performed on annual median values of the response variable aggregated by year to ensure robustness against intra-annual variability and distributional assumptions (Schulz et al., 2017). All analyses and plots were performed using RStudio (version 2024.12.0).

Table 2
Types of habitats assessed in the present and defined according to the EUNIS habitat classification.

Biozone	Substrate	EUNIS2019C
Infralittoral	**Coarse & mixed sediment**	MB35: Mediterranean infralittoral coarse sediment
	Sand	MB55: Mediterranean infralittoral sand
Circalittoral	**Coarse & mixed sediment**	MC35: Mediterranean circalittoral coarse sediment
		MC45: Mediterranean circalittoral mixed sediment
		MD451: Biocenosis of Mediterranean open-sea detritic bottoms on shelf-edge
	Fine mud	MC651: Biocenosis of Mediterranean circalittoral coastal terrigenous muds
		MD651: Biocenosis of Mediterranean offshore circalittoral coastal terrigenous muds
	Muddy sand	MC35: Mediterranean circalittoral coarse sediment
		MD451: Biocenosis of Mediterranean open-sea detritic bottoms on shelf-edge
	Rock or other hard substrata	MC151: Coralligenous biocenosis
		MD151: Biocenosis of Mediterranean shelf-edge rock
	Sand	MC35: Mediterranean circalittoral coarse sediment
		MD451: Biocenosis of Mediterranean open-sea detritic bottoms on shelf-edge
	Sandy mud	MC451: Biocenosis of Mediterranean muddy detritic bottoms
		MD451: Biocenosis of Mediterranean open-sea detritic bottoms on shelf-edge
Bathyal	**Coarse & mixed sediment**	ME35 or MF35: Mediterranean upper bathyal coarse sediment or Mediterranean lower bathyal coarse sediment
		ME45 or MF45: Mediterranean upper bathyal mixed sediment or Mediterranean lower bathyal mixed sediment
	Fine mud	ME65 or MF65: Mediterranean upper bathyal mud or Mediterranean lower bathyal mud
	Muddy sand	ME55 or MF55: Mediterranean upper bathyal sand or Mediterranean lower bathyal sand
	Rock or other hard substrata	ME15 or MF15: Mediterranean upper bathyal rock or Mediterranean lower bathyal rock
	Sand	ME55 or MF55: Mediterranean upper bathyal sand or Mediterranean lower bathyal sand
	Sandy mud	ME65 or MF65: Mediterranean upper bathyal mud or Mediterranean lower bathyal mud

3. Results

3.1. Marine litter density

From 2015 to 2022, a total of 1,742 bottom trawl hauls were carried out along the western Mediterranean continental shelf and slope. During this period, a mean value of 18.49 ± 138.02 kg/km^2 of marine litter was quantified (Table 1). The classification of the marine litter densities in quintiles showed that 20 % of the hauls analyzed had densities of marine litter ranging from 15.57 to 5,055.55 kg/km^2, while the remaining 80 % of the hauls showed values lower than 15.56 kg/km^2.

a. Marine litter categories

Regarding categories, ‘plastic’, ‘fishing gears’, and marine litter classified as ‘other’ were the three main categories observed in the study area with mean values of 4.28 ± 38.98, 4.80 ± 121.48, and 5.38 ± 23.45 kg/km^2 (Table 1; Fig. 2) and were present in 87 %, 50 % and 48 % of the hauls, respectively. It is worth highlighting the presence of 200 kg (5,034.26 kg/km^2) of ‘fishing gears’ in a haul from 2018, a second haul from 2020 with a value of 124 kg (1,553.21 kg/km^2) of plastics, and a third haul from 2021 with 150 kg (1,315.51 kg/km^2) of ‘textiles’.

b. Geographical distribution

Mean values of total marine litter are similar in both demarcations (Table 1). Nevertheless, significant differences were detected within GSAs for total marine litter, ‘plastic’, and ‘fishing gears’ (KW, $p < 0.05$). Regarding total marine litter, significant lower densities were quantified in GSA 5 (8.82 ± 28.71 kg/km^2) and GSA 6N (15.45 ± 114.91 kg/km^2) compared to the section of GSA 1 located in the LEBA demarcation (40.58 ± 93.83 kg/km^2), GSA 1 and 2 (19.88 ± 37.14 kg/km^2), and GSA 6S (29.78 ± 276.75 kg/km^2) (Fig. 2; Dunn test, $p < 0.05$; Table S1). Regarding the density of ‘plastic’, multiple differences were found except between densities quantified in GSA 1 (LEBA) and GSA 6S, and between GSA 5 and GSA 6N, where densities were similar (Fig. 2; Fig. 3a; Dunn test, $p > 0.05$; Table S1). For ‘fishing gears’, GSA 6N showed significantly lower densities (0.17 ± 0.82 kg/km^2) compared to the other GSAs, which ranged from 0.81 ± 2.56 kg/km^2 (GSA 1 in LEBA) to 16.30 ± 2.56 (GSA 6S) (Fig. 2; Fig. 3b; Dunn test, $p < 0.05$; Table S1).

c. Stratum differences

Only ‘plastic’ densities showed significant differences according to bathymetric strata (KW, $p < 0.05$). ‘Plastic’ was found in significantly higher amounts in the shallowest zone, strata A (0–50 m; 10.41 ± 30.30 kg/km^2), compared to strata C (101–200 m; 3.68 ± 13.76 kg/km^2) (Dunn test, $p < 0.05$). Similarly, strata B (51–100 m; 3.49 ± 7.44 kg/km^2), had significantly more ‘plastic’ than strata C, D (201–500 m; 6.58 ± 77.86 kg/km^2), and E (501–800 m; 1.75 ± 3.07 kg/km^2) (Dunn test, $p < 0.05$).

d. Temporal distribution

Differences in total marine litter, ‘plastic’, and ‘fishing gears’ densities between years have been detected (KW, $p < 0.05$). Densities quantified in 2015 (8.68 ± 25.18 kg/km^2) and in 2017 (9.64 ± 26.97 kg/km^2) were significantly lower than in all other years, except for 2020, when similar densities were found (Dunn test, $p < 0.05$). On the other hand, densities quantified in 2019 (16.63 ± 27.79 kg/km^2) were significantly higher than the rest of the years (Dunn test, $p < 0.05$; Table S1). Regarding the temporal trend, total marine litter shows a non-significant increase throughout the study period (Fig. S1; MK, $p > 0.05$, Theil-Sen slope = 0.105).

The ‘plastic’ category quantified throughout the study period showed multiple differences between years. Notably, densities quantified in 2015 (2.21 ± 6.88 kg/km^2) were significantly lower than the other study years, except for 2016, when similar densities were quantified (Table 1; Dunn test, $p < 0.05$). In contrast, the mean value in 2019 (3.86 ± 8.62 kg/km^2) was significantly higher than the values quantified in the rest of the years, except for 2017 and 2018, when similar densities were quantified (Table 1; Dunn test, $p < 0.05$). Regarding the temporal trend, total ‘plastic’ litter shows a non-significant increase throughout the study period (Fig. S2; MK, $p > 0.05$, Theil-Sen slope = 0.026).

According to ‘fishing gears’, the density in 2016 (2.76 ± 20.73 kg/km^2) was significantly lower than the densities quantified in the rest of the years, except with 2017, when similar densities were found (Table 1; Dunn test, $p < 0.05$). Conversely, the densities in 2019 (2.98 ± 17.29 kg/km^2), and 2018 (24.39 ± 341.69 kg/km^2) were significantly higher than the densities quantified in the rest of the years (Table 1; Dunn test,

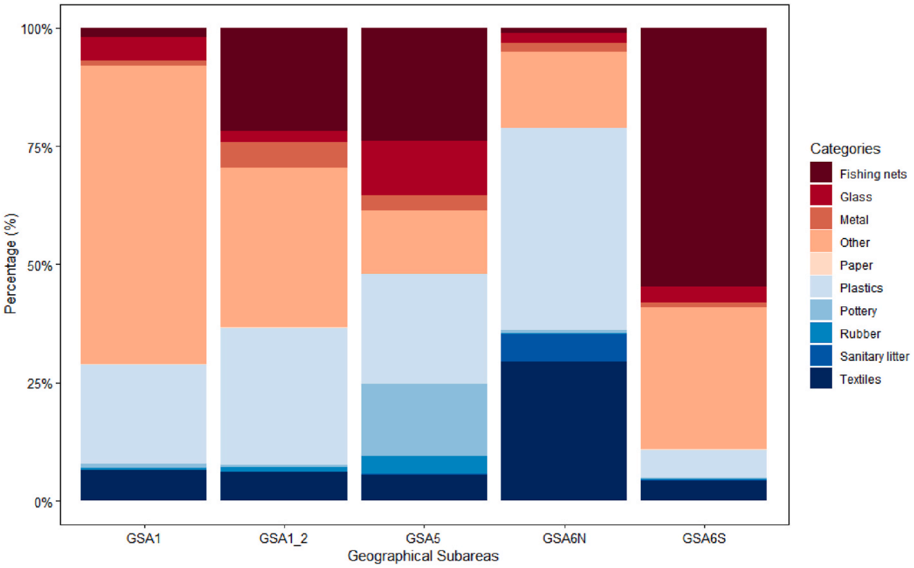

Fig. 2. Stacked barplot representing the percentage of each litter category (fishing gears, glass, metal, other, paper, plastics, pottery, rubber, sanitary litter, and textiles) identified according to geographical subareas.

$p < 0.05$). Regarding the temporal trend in 'fishing gears', there is a non-significant increase throughout the study period (Fig. S3; MK, $p > 0.05$, Theil-Sen slope = 0.003).

3.2. Marine litter in seafloor habitats

The present study quantifies marine litter in different seafloor habitat classifications considered by EMODnet such as the substrate, and the biocinosis of the area considering the European Union Nature Information System habitat classification (EUNIS2019C).

a. Substrate

Total marine litter, 'plastic', and 'fishing gears' densities were significantly different within substrates (KW, $p < 0.05$). Total marine litter density ranged from 8.36 ± 27.07 kg/km^2 in 'sand' substrata to 113.35 ± 699.38 kg/km^2 in 'rock or other hard substrata'. Densities quantified in 'rock or other hard substrata' and in the substrate 'coarse & mixed sediment' (26.40 ± 62.61 kg/km^2) were generally significantly higher than those in other substrata types (Fig. S4; Fig. 4a; Dunn test, $p < 0.05$). In contrast, density quantified in the 'sand' substrate was generally significantly lower than in the other substrate types (Fig. 4a; Dunn test, $p < 0.05$).

Regarding the 'plastic' category, densities ranged from 1.78 ± 5.81 kg/km^2 in 'sand' substrata to 7.59 ± 21.04 kg/km^2 in 'muddy sand' substrata. Densities quantified in the substrate 'coarse & mixed sediment' (6.72 ± 16.96 kg/km^2) were significantly higher than those quantified in the other substrata, except for those quantified in 'muddy sand', which showed similar densities (Fig. 5a; Dunn test, $p < 0.05$).

Regarding 'fishing gears', densities ranged from 0.84 ± 7.55 kg/km^2 in 'fine mud' substrata to 100.88 ± 697.64 kg/km^2 in 'rock or other hard substrata'. Densities quantified in the substrate 'coarse & mixed sediment' (2.98 ± 15.09 kg/km^2) were significantly higher than those quantified in the other substrata, except for those quantified in 'rock or other hard substrata', which showed similar densities. In contrast, densities quantified in the 'muddy sand' (0.93 ± 4.27 kg/km^2) and in the 'fine mud' substrata were significantly lower than most of the substrata of the study area (Fig. 5a; Dunn test, $p < 0.05$; Table S1).

b. Habitats

The habitats from the European Union Nature Information System habitat classification reviewed in 2019 (EUNIS2019C) presented in the study area showed significant differences for total marine litter, 'plastic', and 'fishing gears' densities (KW, $p < 0.05$). Densities ranged from 8.75 ± 12.48 kg/km^2 in 'Biocenosis of Mediterranean shelf-edge rock (MD151)' to 5,055.45 ± NA kg/km^2 in 'Coralligenous biocenosis (MC151)'. Among the 15 different habitats considered, densities recorded in 'Mediterranean circalittoral coarse sediment (MC35)' (12.34 ± 34.51 kg/km^2) and 'Biocenosis of Mediterranean circalittoral coastal terrigenous muds (MC651)' (11.64 ± 28.00 kg/km^2) were significantly lower than those found in most other habitats within the study area. Conversely, the 'Mediterranean upper bathyal coarse sediment or Mediterranean lower bathyal coarse sediment (ME35 or MF35)' habitat showed significantly higher densities (166.10 ± 194.66 kg/km^2) compared to most habitats (Fig. S5; Dunn test, $p < 0.05$; Table S1).

'Plastic' densities in the study area ranged from 2.11 ± 4.28 kg/km^2 in 'Biocenosis of Mediterranean shelf-edge rock (MD151)' to 46.30 ± 43.18 kg/km^2 in 'Mediterranean upper bathyal coarse sediment or Mediterranean lower bathyal coarse sediment (ME35 or MF35)'. 'Mediterranean circalittoral coarse sediment (MC35)' (3.17 ± 11.79 kg/km^2) showed significantly lower values than eight other EUNIS habitats, making it the habitat with the highest number of significantly lower pairwise comparisons (Dunn test, $p < 0.05$; Table S1). In contrast, 'Mediterranean upper bathyal coarse sediment or Mediterranean lower bathyal coarse sediment (ME35 or MF35)' and 'Mediterranean upper bathyal mixed sediment or Mediterranean lower bathyal mixed sediment (ME45 or MF45)' (12.75 ± 12.74 kg/km^2) had significantly higher values than twelve and eleven other habitats, respectively, representing the highest number of significantly higher pairwise comparisons (Dunn test, $p < 0.05$; Table S1).

Regarding 'fishing gears', several statistical differences were detected within habitats (KW, $p < 0.05$). The highest values were recorded in 'Coralligenous biocenosis (MC151)' (5034.26 ± NA kg/km^2), which were significantly higher than those found in nine other EUNIS habitats. In contrast, 'Biocenosis of Mediterranean circalittoral coastal terrigenous muds (MC651)' (1.50 ± 14.51 kg/km^2) showed significantly lower densities compared to eleven other habitats, representing the highest number of significantly lower pairwise differences (Dunn test, $p < 0.05$; Table S1). Only the most relevant pairwise results have been described to simplify the results.

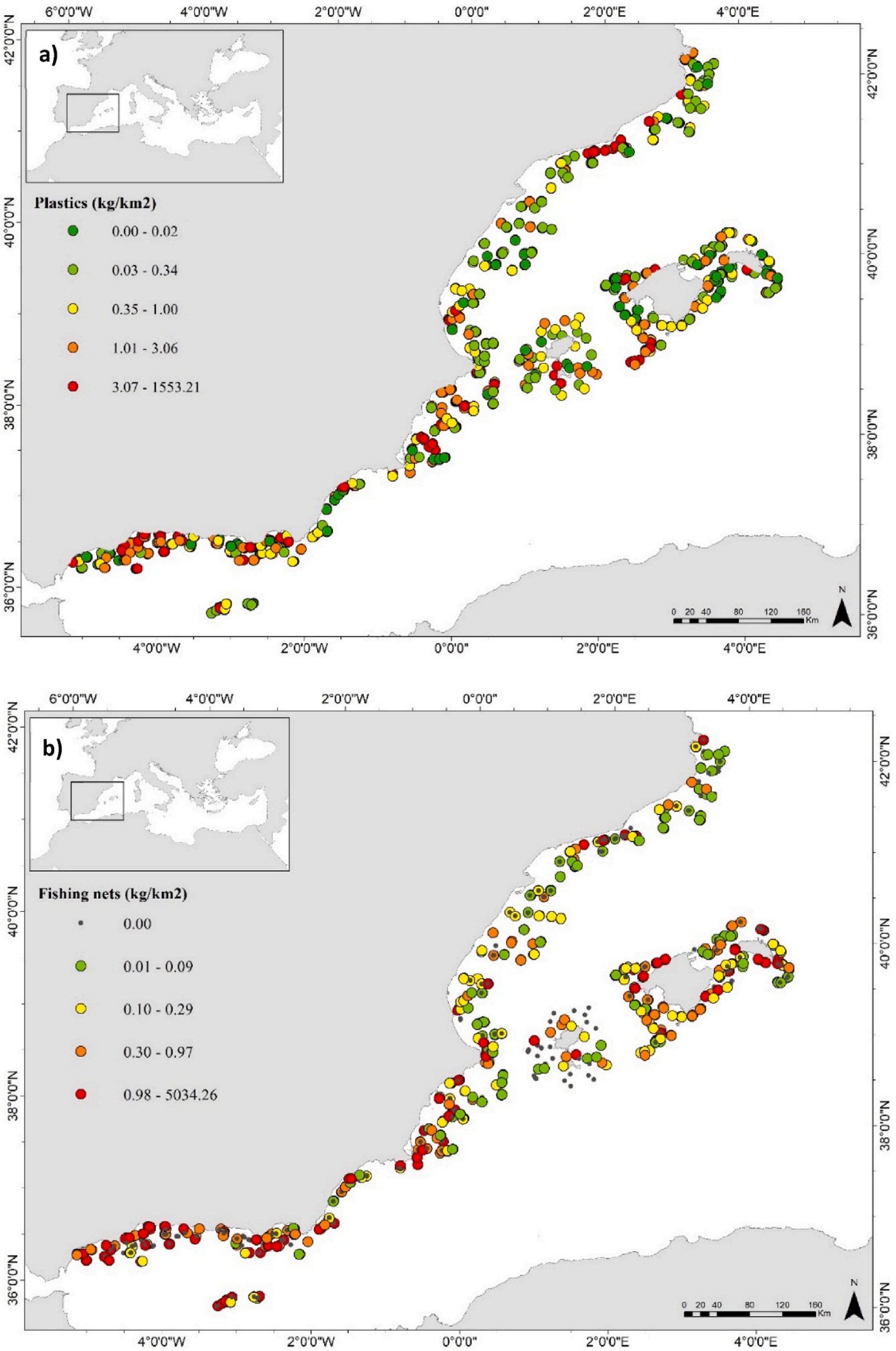

Fig. 3. Densities (kg/km^2) of a) seafloor ‘plastic’ and b) ‘fishing gears’ collected during MEDITS surveys from 2015 to 2022. Classification has been made by using quintiles.

4. Discussion

This study aims to analyze the density of marine litter along the continental shelf and slope, focusing attention on the density of plastic and fishing gears along different types of substrates and habitats making up the biocinosis of the study area. The extensive geographic coverage encompasses all Spanish Mediterranean waters, enabling us to evaluate the potential impacts of marine litter on its seafloor. As far as we know, there are several studies carried out in the western Mediterranean Sea quantifying the density of marine litter on the seafloor (García-Rivera et al., 2018, 2017), and even analyzing its impact on benthic marine organisms (Alomar et al., 2020b), but there are no studies including the biocinosis of the study area.

4.1. Marine litter density

a Geographical distribution

Marine litter is ubiquitously present along the entire seabed of the western Mediterranean Sea. In the study area, differences at lower geographical area classification have been found, suggesting that the spatial distribution of marine litter at the seafloor can be affected by the hydrodynamics, the geomorphology, and even the seafloor typology (Canals et al., 2021; Fakiris et al., 2022).

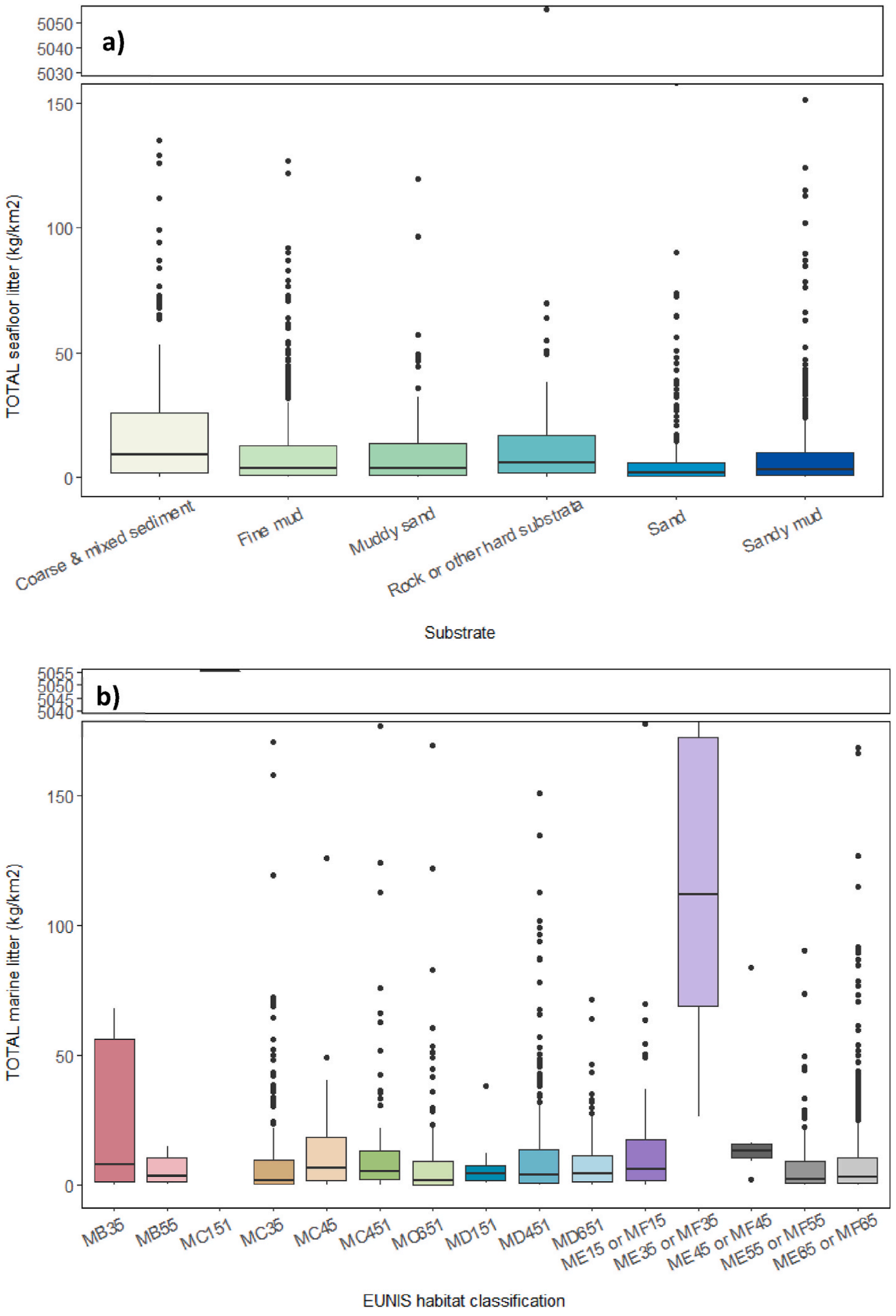

Fig. 4. Boxplot of the mean values (±SD) of total marine litter quantified (kg/km^2) during MEDITS surveys from 2015 to 2022 and according to a) substrate, and b) EUNIS habitat classification.

When analyzing the specific locations of hauls at a finer scale, areas near highly populated and touristic cities like Barcelona and Valencia, which also host major commercial ports, show the highest density of seafloor marine litter, as observed in other Mediterranean cities like Marseille in France or the densely urbanized regions of Campania and Liguria in Italy (Angiolillo et al., 2023; Spedicato et al., 2019). Contrarily, hauls from the surroundings of the Ebro Delta have the lowest density of marine litter with a mean value of 6.30 ± 38.99 kg/km^2 and ranging from 0 to 365.40 kg/km^2. The Ebro Delta is one of the largest wetland areas in the western Mediterranean, and the Ebro River is the largest river on the Iberian Peninsula and one of the largest in the Mediterranean region. In this context, riverine currents are considered potential drivers of marine litter transport, facilitating its movement across the continental shelf and towards deeper areas, rather than allowing its accumulation in coastal zones (Ramirez-Llodra et al., 2013). From this perspective, the Ebro River seems to have an important influence on the distribution of seafloor marine litter along the western Mediterranean Sea, transporting the marine litter to near emplacements.

‘Plastic’, ‘fishing gears’, and marine litter classified as ‘other’ (mainly composed of clinker) are the three main categories found in the seafloor of the study area, and were present in 87 %, 50 % and 48 % of the hauls, respectively. The prevalence of plastic and items related to fishing activities along the seafloor has already been reported in previous studies (Barry et al., 2023; Pham et al., 2014). In coastal seas of North West Europe, in 25 years (1992–2017), 63 % of the 2461 trawls contained at least one plastic litter item (Maes et al., 2018), and in 1279 Mediterranean surveyed stations the frequency of occurrence ranged from around 58 % in Sardinian waters to about 99 % in the Gulf of Lions (Spedicato

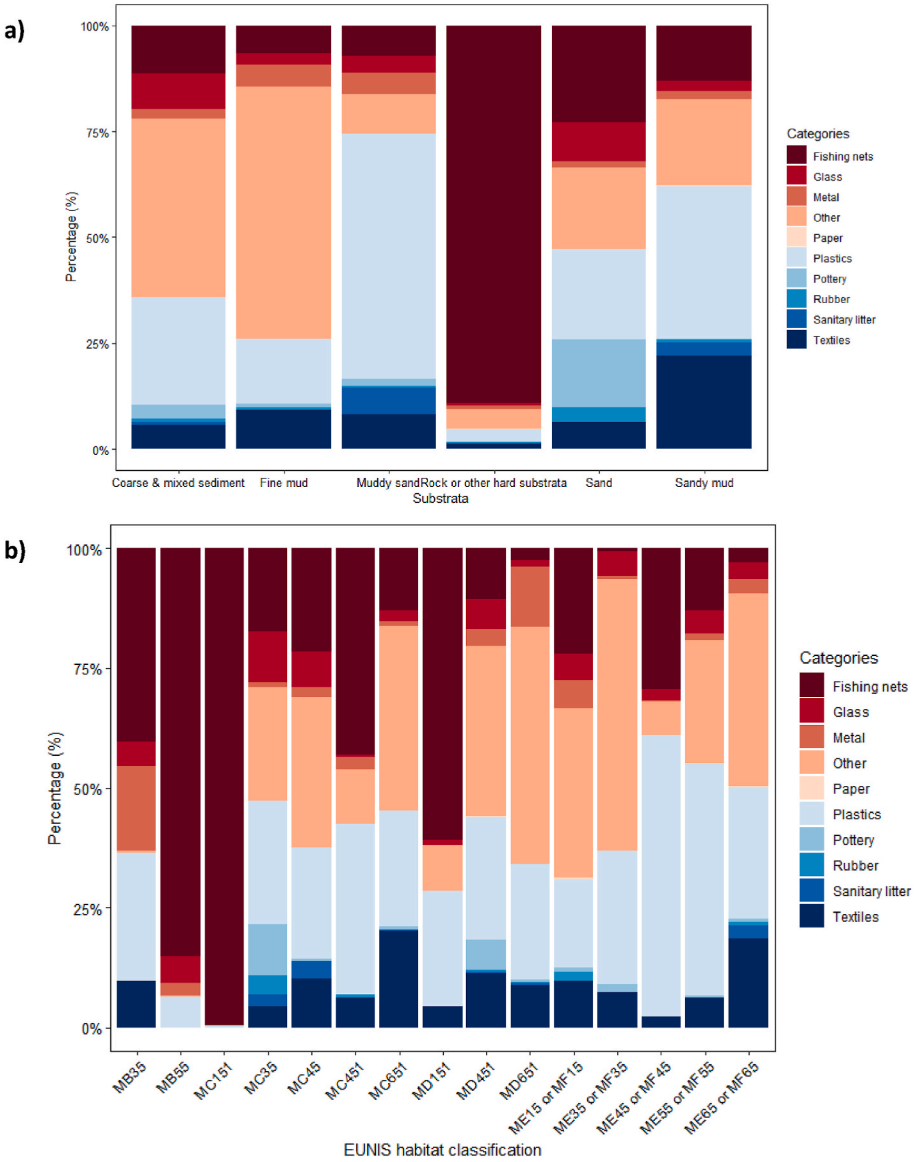

Fig. 5. Stacked barplot representing the percentage of each litter category (fishing gears, glass, metal, other, paper, plastics, pottery, rubber, sanitary litter, and textiles) identified according to a) substrata and b) EUNIS habitat classification.

et al., 2019). To understand its prevalence in the marine environment, particularly along the seafloor, it must be considered that specific conditions in this compartment, such as low UV light exposure, consistently low temperatures, and a low-energy regime, especially in deep areas, slow the degradation rate of certain marine litter items, increasing their persistence in this environment (Corcoran, 2015). The plastic densities quantified, although worrying, are lower than densities collected in the central western Mediterranean Sea under the same MEDITS protocol and gear, specifically along the seafloor of Sardinian waters, where authors reported mean values of 7.35 ± 2.37 kg/km^2 (Alvito et al., 2018). However, this study includes fishing-related items in the plastic fraction, comprising 9.4 % of this litter fraction, and it is likely that if in the study the same plastic categories had been considered, mean values would be more similar amongst study areas. To consider, values reported in this study are within the range of the previously quantified in the study area, specifically in the Gulf of Alicante, which is included in the GSA6 S from the LEBA demarcation, where an abundance range of 0–11.6 kg/km^2 of plastic seafloor litter during 2014 was reported (García-Rivera et al., 2017). To highlight, this study builds upon the findings of García-Rivera et al. (2017), providing a continuation of that study and further contributing to the understanding of seafloor litter distribution in the region.

Regarding ‘fishing gears’, these items are commonly made of plastic material; therefore, it must be added that they are highly durable objects with strong resistance to environmental factors (Corcoran, 2015). Within our study area, lower densities have been quantified in ESAL than in LEBA demarcation. As far as we know, only one study performed in the Mediterranean Sea in the Balearic Islands (GSA 5) considered the category of fishing gears separately from the plastic fraction and reported lower densities of fishing gears (1.50 ± 0.47 kg/km^2; Alomar et al. (2020a)) than the density reported in the present study in the same study area (GSA 5; 2.13 ± 17.39 kg/km^2). In this sense, it must be considered that some studies indicated that fishing gears dominated in areas where fishing activities are intense, relating the presence of derelict fishing gears to local fishing activities (Enrichetti et al., 2020; Pham et al., 2014), and highlighting the need for specific measures to reduce this type of marine litter from fishing activities. Other studies include this category in the plastic or metal fraction (Alvito et al., 2018; García-Rivera et al., 2018, 2017; Strafella et al., 2019), which makes it difficult to know the real presence of this type of litter along the seafloor as well as comparing between study areas. The scarcity of studies analyzing fishing gears as a single category disagrees with the requirements established by the policies involved. The Directive (EU) 2019/904 of the European Parliament and of the Council of June 5, 2019 on the reduction of the impact of certain plastic products on the environment, expresses that European Member States "*shall monitor fishing gear containing plastic placed on the market of the Member State as well as waste fishing gear containing plastic collected*". To respond to these policies, future studies must consider this category of marine litter separately to evaluate the real impacts, establish specific mitigation measures, and evaluate the effectiveness of the implementation of these measures.

According to the category 'other', in our study, mainly composed of clinker, resulted in the third main category of marine litter quantified along the seafloor from the study area. High densities of clinker have been previously detected in the western Mediterranean Sea (Alomar et al., 2020a; García-Rivera et al., 2018; Ramirez-Llodra et al., 2013). In this sense, clinker, together with other high-weight debris such as glass and metal items, is expected to be found close to the source due to its rapid settling on the seafloor (Pham et al., 2014). Ramirez-Llodra et al. (2013) already detected large quantities of clinker on those hauls carried out within the route of major shipping routes from Marseille to Oran and the Suez-Gibraltar corridor, demonstrating that the accumulation occurred as a consequence of steam ships dumping the burnt coal from the late 18th century and well into the 20th century.

b Stratum differences

The present study indicates that the highest densities of the plastic category are observed along the shallower continental platform (strata A: 0–50 m) and intermediate bathymetric depth seafloor (strata D: 201–500 m). The shallower water represents a marine region of high ecological diversity, and complex oceanographic conditions, and is often affected by multiple anthropogenic activities due to its proximity to urban areas or the establishment of aquaculture facilities. Previous studies carried out in other Mediterranean shallower stations have also reported to be more affected by the presence of marine litter, decreasing in density as the depth increased, probably because of the highest influence of the inland or coastal sources (Alvito et al., 2018; Cau et al., 2022; Pasquini et al., 2016; Strafella et al., 2015). The Spanish Mediterranean coast suffered extensive coastal urbanization and mass tourism, particularly between 1960 and 1990. Approximately 44 % of its population lives in coastal areas, and the population density on the coast is four times higher than the national average, with an increase of 300 % during summer months (Ministerio de Hacienda y Administraciones Públicas, 2012). In 2007, 60 million tourists visited Spain, with three-quarters heading directly to the coast, reflecting the ongoing pressure from both local populations and tourism on coastal areas, highlighting the need for sustainable strategies to protect these regions (Dias et al., 2013), and evidencing the pressure that these regions have to manage.

Additionally, the densities quantified at intermediate bathymetric depth strata suggest that other factors not involved in the anthropogenic activities carried out in coastal waters influence the accumulation of marine debris in these areas. For example, in the Mediterranean Sea, the highest densities and biomass of high commercial species such as the Norway lobster *Nephrops norvegicus* and the deep-water pink shrimp *Parapenaeus longirostris* are located at depths ranging from 200 to 500 m (Abelló et al., 2002); hence, this bathymetric range may experience higher fishing pressure, which may lead to greater impacts in terms of marine litter. Moreover, a study performed by ROV on the rocky banks of an Ecologically or Biologically Significant Area (EBSA) in the Strait of Sicily located in the central Mediterranean Sea reveals that the average accumulation of marine litter was higher at deeper depths (>100m; 5.2 items/100 m^2) than at shallower depths (<100m; 0.71 items/100 m^2), and showed the potential role that the seafloor morphology has on the accumulation of marine litter due to the highest amounts of litter found in rocky habitats, where complex reliefs such as boulders and outcrops may cause damage or loss of fishing gears, the most common type of litter identified (Consoli et al., 2018). These results evidence the requirement to consider multiple variables such as the activities carried out in the study area, not only the bathymetric depth, to understand the accumulation of marine litter on the seafloor.

c Temporal distribution

Multiple differences within years have been detected, and higher densities of total and plastic marine litter were quantified in 2020, matching the year when 124 kg were quantified in a single haul. The presence of hauls in which disproportionate densities of marine litter are found is usual (Maes et al., 2018), suggesting that great amounts of marine litter can accumulate as a result of a specific event, such as a punctual discharge, and/or environmental conditions. In our study, no significant temporal trends were detected. Nevertheless, it must be mentioned that according to geographical sub-areas, the plastic fraction quantified in Balearic Islands (GSA 5) was 2.04 ± 5.59 kg/km^2 a value slightly lower than the 2.73 ± 0.26 kg/km^2 reported by Alomar et al. (2020a) that analyzed the seafloor litter at the same area for the 2001–2015 sampling period. An slight and continuous decreased trend in total and plastic marine litter was previously reported in other studies (Fakiris et al., 2022; García-Rivera et al., 2018) and can be considered a sign of improving the marine environment, probably due to the increase in awareness of the problem of plastics in the marine environment among citizens and the establishment of different actions that reduce the input of marine litter into the marine environment and also increase the output of this type of pollution. However, the continuity of the monitoring of the seafloor litter is required because of the multiple factors affecting the presence and distribution of marine litter along the seafloor.

4.2. *Habitats*

a Substrate affected

All types of substrata of the western Mediterranean Sea, from fine mud to coarse sediment, are affected by marine litter. The highest densities have been quantified in 'rock or other hard substrata' (113.35 ± 699.38 kg/km^2), followed by 'coarse & mixed sediment' (26.40 ± 62.61 kg/km^2), and the lowest densities in 'sand' substrata (8.36 ± 27.07 kg/km^2), showing that rocky and sandy substrates play different roles in the retention of marine litter. According to the EUNIS definition, coarse sediments "*include coarse sand, gravel, pebbles, shingle and cobbles which are often unstable due to tidal currents and/or wave action*". In addition, mixed sediments "*range from muds with gravel and sand components to mixed sediments with pebbles, gravels, sands, and mud in more even proportions*". Hence, results from the present study suggest that the predominance of pebbles and gravel on the seafloor can increase the accumulation capability of marine litter in comparison to muddy or sandy substrata, possibly linked to the capability of the marine litter items to get trapped, as occurs in rocky substrata. In contrast, sandy substrata *"typically lack a significant seaweed component,"* exhibit a dynamic nature, and are constantly reshaped by hydrodynamic forces, suggesting a limited ability to retain marine litter. Additionally, in soft-bottom habitats such as sand or mud, the lower retention observed may not only reflect reduced trapping capacity but also the potential burial of litter items. Depending on local hydrodynamics and sediment fluxes, marine litter can become covered by sediment layers, hindering its detection and contributing to the underestimation of actual seafloor accumulation in these dynamic environments (Cerrillo-Escoriza et al., 2023).

Among the ecological implications of this unequal ability to trap and retain marine litter, this study considers, on one hand, the potential number of individuals and species in terms of biodiversity that could be affected by the presence of marine litter, and on the other hand, the sensitivity of specific habitats or species to the pressures imposed by the presence of marine litter. Regarding the first approach, the composition and organization of benthic fauna, both sessile and mobile, are influenced by environmental gradients that vary with the seasons, depth, substrate type, and interactions among organisms (Gili et al., 2014). In this sense, a previous study demonstrated that a diverse seafloor, shaped by various morphologies, helps maintain high levels of deep-sea biodiversity (Zeppilli et al., 2016). In particular, rocky habitats have been shown to significantly influence benthic faunal composition, with greater densities and diversity linked to hard, rocky substrates (Almond et al., 2021). This is likely due to the architectural complexity of rocks, which provide refuges and barriers that facilitate the dispersion of mobile species (Kostylev et al., 2005). Considering the theoretical greater biodiversity in complex substrates, a greater number of individuals are potentially affected in our study area due to the higher densities identified in this type of substrate. In terms of sensitivity, some species are more vulnerable to the damage resulting from marine litter. For instance, deep-water fishing significantly impacts rocky seabed habitats as surveys reveal that lost fishing gear is a major source of damage, correlating with entangled and overgrown corals, while the presence of broken coral colonies and disturbed habitat-forming species highlights the harmful effects of these activities (Bo et al., 2014).

The main limitation of the present study is that the bottom trawls are only performed on soft bottoms, making it impossible to estimate the density of marine litter in rocky, abyssal or even protected areas. The use of other methodologies non or less invasive such as ROV or the assessment by scuba divers are applied and performed (Compa et al., 2022; Consoli et al., 2018; Enrichetti et al., 2020; Incera et al., 2024) and can be used to compare within studies. In this sense, the study performed by ROV between 30 and 220 m depth along the Ligurian coast detected the highest densities of marine litter on deep coastal rocky shoals (Enrichetti et al., 2020), and differences between substrata were also confirmed in the study performed by Melli et al. (2017) in a Site of Community Importance in the north-western Adriatic Sea, and by Compa et al. (2022) in a Mediterranean Marine Protected Area, which found a significantly higher density of marine litter on rocky bottoms compared to soft substrates. The main hypothesis is that marine litter gets trapped between the rocks, as suggested by our results. These studies highlight the importance of integrating observations collected through bottom trawls with other methodologies to evaluate all types of substrata and have a complete view of the distribution of marine litter along the seafloor.

b Habitat affected

There are multiple interactions between marine litter and benthic habitats at community or individual levels such as the physical covering, the ingestion of marine litter particles, or the entanglement with plastic items or fishing gears (Angiolillo et al., 2015; Bo et al., 2014; Melli et al., 2017). From the 23 habitats described by the European Union Nature Information System (EUNIS) in the western Mediterranean Sea, only 15 have been analyzed as they correspond to those habitats in which scientific hauls have been performed. In our study, the bathyal coarse sediment (‘ME35 or MF35: Mediterranean upper bathyal coarse sediment or Mediterranean lower bathyal coarse sediment’) is the habitat most affected by the presence of marine litter. A total of 11 hauls have been conducted in this specific habitat, all of them located in the Golfo de Vera between 101 m (lower limit of strata C) and 500 m (upper limit of strata D) and with high densities of litter (ranging from 63.53 to 728.03 kg/km^2) with no predominant litter category, suggesting that the morphological structure of this type of seabed promotes the marine litter accumulation in general. In contrast, ‘MC35: Mediterranean circalittoral coarse sediment’ and ‘MC651: Biocenosis of Mediterranean circalittoral coastal terrigenous muds’ were the least affected habitats, suggesting that these substrate types have a lower capacity to retain marine litter. Moreover, the circalittoral environment overall appears to be less impacted, potentially reflecting its dynamic nature. These results most promote the investigation of the physical and hydrodynamic characteristics of bathyal in comparison to circalittoral environments to understand how seabed morphology and water movement influence litter retention.

The presence of marine litter on the seafloor can adversely impact benthic organisms that are vulnerable to habitat disturbances such as those provoked by the interaction between some species with marine litter. Additionally, derelict fishing gear can have persistent ecological impacts, as it continues to entangle, damage, or kill marine organisms long after being discarded (Beneli et al., 2020) affecting several types of marine organisms from species of special conservation concern to structuring species such as coral reefs or sensitive habitats (Chiappone et al., 2005; Consoli et al., 2018; Pham et al., 2014). Considering all the reported impacts, the presence of marine litter in the study area demonstrates the potential damage that the presence of marine litter can cause to the benthic environment, and emphasizes the need for stronger mitigation measures, particularly to prevent derelict fishing gear, to sustain a healthy benthic ecosystem and, in turn, the entire marine environment. Additionally, future studies should explore the ecological consequences of litter accumulation in coarse sediment habitats, particularly on benthic communities, to evaluate habitat-specific vulnerability. Moreover, inconsistencies detected in the available habitat classification layers highlight the need to improve the accuracy and resolution of habitat mapping to ensure more robust spatial analyses.

5. Conclusions

The present study reaffirms that plastics and fishing gears are the most predominant litter items on the seafloor, particularly in coarse sediment habitats and in the bathyal environment. This is likely related to their morphological structure and inherent characteristics, which may promote litter retention, but also increase the vulnerability of associated benthic species. Seafloor characteristics, including substrate type, habitat category, and proximity to local litter inputs, play a crucial role, indicating that no single factor can fully explain the observed distribution. Coarse & mixed sediments, along with specific habitats like the Mediterranean bathyal coarse sediment (upper and lower), appear to be more impacted.

One of the main limitations of this study is that bottom trawl surveys can only be conducted on soft substrates, resulting in an underrepresentation of rocky or hard-bottom habitats. As a consequence, litter accumulation in these areas remains poorly characterized. To address this gap, future studies should integrate data from alternative observation methods, such as ROVs or towed camera systems. Future efforts should also focus on identifying litter input sources and transport pathways, supported by long-term monitoring and improved habitat mapping, to better understand spatial and temporal patterns of accumulation.

CRediT authorship contribution statement

Beatriz Rios-Fuster: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Carme Alomar:** Writing – review & editing, Validation, Supervision, Project administration. **Salud Deudero:** Writing – review & editing, Validation, Resources, Project administration, Funding acquisition, Conceptualization.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2025.126940.

Data availability

Data will be made available on request.

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