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From shallow to deep water: A large-scale assessment of seafloor marine macrolitter in the Italian seas by ROV-imaging

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ABSTRACT

The seafloor is the ultimate sink for most litter worldwide. Although significant efforts have been made over the past two decades to assess the impact of litter on marine ecosystems, collecting quantitative data using standardised, comparable protocols remains limited. A large-scale dataset, derived from over 56 oceanographic surveys conducted between 2007 and 2023 using remotely operated vehicles (ROVs) in the Italian seas (Mediterranean Sea), enabled a comprehensive census of seafloor marine litter across shallow to bathyal zones (40–2129 m). The explorations primarily focused on rocky areas, including continental shelf reliefs, canyons, and offshore seamounts. The ROV-imaging dataset enabled the collection of important information on litter quantity, composition, patterns of geographic and bathymetric distribution, effects on benthic communities, and relationships with several environmental and anthropogenic variables. 10,982 items were recorded, and litter abundance reached 16.1 items 100 m^{-2} (average 1.5 ± 0.1 items 100 m^{-2}), with significant local differences in quantity and composition. Only 8.6% of the investigated sites were litter-free, while 1.0% had abundances exceeding 10 items 100 m^{-2}. Fishery-related litter (mainly lines and ropes) was the most common type, accounting for ≈70.8% of the total items. This work provides the first comprehensive picture of seafloor marine litter in the Italian seas. In addition, it shows that 87% of sites exceeded the European threshold (expressed as litter density) for seafloor marine litter, recently defined under the Marine Strategy Framework Directive Descriptor 10. The results underscore the need for urgent, targeted measures to manage marine pollution and reduce inputs of environmental litter.

1. Introduction

Marine litter is an urgent, sensitive, and growing global issue from both ecological and socioeconomic perspectives (Vieira et al., 2015). It is defined as any persistent, human-made solid material, whether manufactured or processed, discarded, disposed of, abandoned, or lost in the marine and coastal environment (UNEP, 2009). Inadequate waste management and infrastructures, combined with irresponsible human behaviour, have led to its widespread distribution, even in remote areas (e.g., Barnes et al., 2010; Pham et al., 2014; Chiba et al., 2018; Canals et al., 2020; Ramírez-Llodra, 2020; Nakajima et al., 2021; Abel et al., 2023; Zhu et al., 2024; Hanke et al., 2025a).

Over recent decades, growing awareness of ocean plastic pollution concentrations has heightened concern about its ecological and human health impacts, prompting the prioritisation of marine litter-particularly plastic-on policy agendas (Boucher et al., 2020; UNEP, 2021; EU Plastics Strategy; EU Zero Pollution Action Plan; https://www.unep.org/inc-plastic-pollution). Consequently, assessment and monitoring of litter have become central to regulation and research (Sandra et al., 2025). However, comprehensive evaluation across marine environmental compartments (beaches, surface, seabed, and water column) and biota requires extensive sampling (Laist, 1997; Gall and Thompson,

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2015; Haarr et al., 2022).

The deep ocean is one of the most challenging environments to study, with limited access leading to centuries of litter disposal on the seafloor (Miyake et al., 2011; Ramírez-Llodra et al., 2011; Angiolillo, 2019). As a result, it has become a major sink for marine litter, where waste persists and degrades slowly, impacting benthic ecosystems (Thompson et al., 2004; Canals et al., 2020; Hanke et al., 2025b). However, data on its distribution, composition, and ecological effects remain scarce due to the cost and difficulty of deep-sea research. Existing data are often inconsistent, as they are typically collected opportunistically during studies with other primary objectives (Hanke et al., 2025a).

This is especially evident in the Mediterranean Sea, one of the world's most polluted marine basins (Barnes et al., 2009; Deudero and Alomar, 2015; Còzar et al., 2015; Jambeck et al., 2015; Ramírez-Llodra et al., 2018). Intense human activity, including maritime traffic and fisheries, has led to widespread and heterogeneous litter distribution (Liubartseva et al., 2018). Over 220,000 vessels (container ships, tankers, general cargo ships, and passenger ships) cross the region annually, representing 15–30% of global maritime traffic (Ramírez-Llodra et al., 2013; Randone et al., 2019). Combined with river inputs and dense coastal population, including major cities and heavy international tourism, these pressures make the Mediterranean a major reservoir of marine pollution (Galgani et al., 2019).

In recent decades, considerable effort has been made to assess the distribution and impacts of marine litter in the Mediterranean (e.g., Fortibuoni et al., 2021; Arcangeli et al., 2025; Angiolillo et al., 2023a, b). However, quantitative data on deep-sea seafloor litter remain limited due to the high cost and technical challenges of deep-sea research (e.g., Pierdomenico et al., 2019; Enrichetti et al., 2020; Dominguez-Carrió et al., 2020; Martynova et al., 2024). Most data on benthic macrolitter (> 2.5 cm) come from opportunistic trawl bycatch, which is spatially biased towards fishing grounds and soft bottoms and involves destructive methods (e.g., Hess et al., 1999; Galgani et al., 2000; Keller et al., 2010; Watters et al., 2010; Spedicato et al., 2019; Canals et al., 2020). Inconsistent sampling approaches (use of different gear) further limit comparability across the basin. Large-scale mapping efforts are rare, especially in deeper areas. Programs such as the Mediterranean International Trawl Survey (MEDITS) would provide extensive data, but access is restricted, and surveys are limited to depths of 800 m (Spedicato et al., 2019).

Recent advances in underwater imaging technologies, including submersibles, remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), and towed cameras (TCs), enable non-destructive seafloor surveys, allowing quantification of litter and its interactions with marine organisms (Bo et al., 2014; Angiolillo and Fortibuoni, 2020; Canals et al., 2020). However, standardised and comparable protocols remain limited, and existing guidance (GESAMP, 2019; MSFD Technical Group on Marine Litter, 2013; MSFD Technical Group on Marine Litter, 2023) would benefit from greater harmonisation and international coordination (Chiba et al., 2018).

In this context, the European Marine Strategy Framework Directive (MSFD, 2008/56/EC) provides a key framework for monitoring marine litter and assessing ecosystem health to protect biodiversity (Tunesi et al., 2013; Danovaro et al., 2020). Under Descriptor 10 – Marine litter (D10), MSFD requires evaluation of anthropogenic pressures, including marine litter. In the Mediterranean, implementation has focused mainly on coastal and shallow-water habitats, with limited coverage of deeper habitats (Fabri et al., 2019; Danovaro et al., 2020; Kazanidis et al., 2020). Currently, only Italy and Spain conduct targeted deep-seafloor monitoring in vulnerable ecosystems (i.e., coralligenous reefs, deep coral forests, and scleractinian cold-water corals (CWCs)), using ROV images to assess litter distribution and its interactions with benthic communities (Angiolillo et al., 2023a, b). The impact of marine litter on benthic communities in the Mediterranean Sea are well documented (e.g., Bo et al., 2014; Cau et al., 2017; Fabri et al., 2018, 2019; Enrichetti et al., 2019; Angiolillo and Fortibuoni, 2020; Ferrigno et al., 2021; Pierdomenico et al., 2021; Aguilar et al., 2022; Martínez-Dios et al., 2025). Abandoned, lost, or otherwise discarded fishing gear (ALDFG) can damage benthic fauna, especially large, branched species, through entanglement, breakage, abrasion, eradication, favouring epibionts, and necrosis (Bo et al., 2014; Angiolillo et al., 2015; Galgani et al., 2018; Consoli et al., 2018; Enrichetti et al., 2019; Angiolillo and Fortibuoni, 2020; Pierdomenico et al., 2021). Other litter alter habitats by introducing hard substrata for settlement, transporting invasive species, smothering substrata or species, and fragmenting into microplastics (Anastasopoulou and Fortibuoni, 2019). However, studies beyond the continental shelf remain scarce, despite evidence that litter, particularly plastic, is accumulating even in the deep seafloor (Mordecai et al., 2011; Pham et al., 2014; Chiba et al., 2018; Angiolillo et al., 2021; Pierdomenico et al., 2023; Carreras-Colom et al., 2024; Hanke et al., 2025a, Hanke et al., 2025b; and references therein).

Given these challenges, there is an urgent need to assess and monitor marine litter and its ecological effects in deep-sea habitats, where large-scale, harmonised datasets remain scarce. Italian seas, characterised by diverse seabed landscapes and intense human activity, offer a valuable case study. Data collected over 18 years (2007–2023) using ROV-imaging provides a comprehensive, standardised assessment of marine litter up to 2129 m across ~600 nautical miles, including its quantity, composition, geographic and bathymetric distribution patterns, and effects on benthic communities. Additionally, to evaluate the litter impact, data from depths up to 200 m were compared with the recently established EU-level threshold value (TV) within the MSFD framework used to define the D10 Good Environmental Status (GES).

2. Materials and methods

Using a standardised approach, an extensive dataset was analysed to define the large-scale distribution of seafloor litter in the circalittoral and bathyal zones (40–2129 m) of the Italian seas (Mediterranean Sea). Data were collected from over 56 oceanographic surveys conducted between 2007 and 2023 using remotely operated vehicles (ROVs) as part of various scientific projects (Table 1). The explorations mainly targeted areas with hard substrata, including continental shelf reliefs, canyons, and offshore seamounts, and only marginally the surrounding soft bottoms. All ROVs were equipped with high-definition video cameras, underwater acoustic tracking and positioning systems, Ultra-Short Baseline (USBL), and laser beams at known distances.

The dataset comprised 683 ROV transects, each corresponding to a different site, located in six macroareas (Ligurian Sea – LIG, North-central Tyrrhenian Sea – NCT, South Tyrrhenian Sea – ST, Sicily Channel – SC, Sardinian Sea – SARD, and Adriatic-Ionian seas – ADR/ION), including nine wrecks and five offshore seamounts.

The presence of seafloor litter and its potential impact on benthic species were evaluated by analysing the ROV footage, reporting its quantity (number), density (items 100 m^{-2}), composition, and entanglement event. To calculate the area covered by each ROV transect, the tracks were mapped in QGIS, and laser beams were continuously used for scale calibration. Irrelevant video segments (e.g., ascent/descent in the water column, parts with poor visibility, variations in ROV altitude, pitch, and camera angle) were excluded from the analysis. On average, transect lengths ranged from 350 m to 750 m (median = 540 m), depending on the seafloor topography and survey goals, except in nine cases, where the tracks were more than 3000 m long. The transect width ranged from 0.5 to 2 m and was calculated for each transect as the mean width of valid segments, using the laser beams as a reference. The surveyed area was estimated by multiplying the transect length by the average width. Overall, the study covered 822,704 m^2 of seafloor and processed approximately 736 h of video footage. Video editing and analysis were carried out using Final Cut Pro X (version 10.4) and VLC (VideoLAN).

All macrolitter items (> 2.5 cm) visible on the seafloor (thus excluding buried objects) along each track were counted and classified

Table 1
Technical information on the surveys conducted in the investigated areas. LIG = Ligurian Sea, NCT = North-central Tyrrhenian Sea, ST = South Tyrrhenian Sea, SARD = Sardinian Sea, SC = Sicily Channel, ADR/ION = Adriatic-Ionian seas.

Project	Year	Macroarea	Survey (no.)	Sites (no.)	ROV type
MoBioMarCal	2007–2009	ST, ADR/ION	3	116	Pollux
CWCs	2007, 2010	ADR/ION	2	3	PlutoPalla
TYSEC	2009	NCT	1	8	Pollux
Biodiversità Canale di Sicilia	2010	SC, ADR/ION	3	18	Pollux
GEOTHERMAL	2010, 2011	ST	2	18	Pollux
Corallo rosso	2010–2012	LIG, NCT, ST, SARD, SC	9	110	Pollux
Relitti	2011, 2012	SC	2	7	Pollux
Corallo rosso Sardegna	2011, 2013	NCT, SARD	2	65	Pollux
Scilla	2011	ST	1	4	Pollux
Concordia	2012	NCT	1	10	Pollux
Greenpeace Canale Sicilia	2012	SC	1	7	Pollux
Vulcani Panarea	2013	ST	1	11	Pollux
Ecosafimed	2014	NCT, ST	2	35	Pollux
AMP Milazzo	2014	ST	1	14	Pollux
Banchi Canale di Sicilia	2014	SC	1	15	Pollux
GEOCAL	2014	ST	1	5	Pollux
Montalto di Castro	2014	NCT	1	2	Pollux
MSFD_2015	2015	LIG	1	34	Pollux
RAMOGE 2015	2015	LIG	1	5	Pollux
MSFD_2016	2016	LIG	1	21	Pollux
Biomount	2017, 2018	LIG	2	15	MultiPluto
MSFD_2017	2018	LIG	1	33	Blu ROV 2
RAMOGE 2018	2018	LIG	1	4	Victor 6000
Seamount 2018	2018	SC	1	15	Perseo
MSFD_2018	2019	LIG	1	7	Chinoox
PlasticBusterAMP	2020	NCT	1	7	Perseo
MSFD_CWC	2020–2023	LIG, NCT, ST, ADR/ION, SC	7	53	Perseo
AMP Maratea	2021	ST	1	7	Perseo
UniGe_Curiosity	2021	LIG	1	14	MultiPluto
RAMOGE 2022	2022	LIG	1	3	Perseo
MoRinet	2023	NCT, SARD	2	17	Perseo

into five main categories: i) artificial polymer materials; ii) other (including glass/ceramics, metal, cloth/textile, processed/worked wood and undefined); iii) lines and ropes; iv) nets; and v) other fishing-related items, in line with the main litter categories found on the seabed (Angiolillo et al., 2021; Fleet et al., 2021). Particular attention was paid to avoid double-counting lines and ropes, mainly longlines, which may extend for tens to hundreds of meters.

Moreover, the depth at which each object was observed was recorded to assess the bathymetric distribution of marine litter. Five depth ranges were selected, corresponding to the deepest part of the continental shelf (40–80 m), the shelf break (80–150 m), two upper bathyal ranges on the continental slope and seamounts (150–250 m and 250–500 m), and the lower bathyal (>500 m).

Finally, the data up to 200 m depth were compared with the established threshold value (TV) for litter allowed on the seafloor at the EU level under the MSFD framework. In areas monitored visually in waters up to 200 m, the threshold must be no more than 1000 items km^{-2} (EU news, 2025).

2.1. Explanatory variables

Potential candidate variables for predicting litter abundance and distribution in the study area were selected, comprising both environmental and anthropogenic factors.

Environmental parameters included substratum type, visually classified into the categories i) sand and mud, ii) detritus, iii) outcropping rocks, iv) coralligenous accretions, v) thanatocoenosis, vi) coral bioconstruction and rubble, and vii) artificial (e.g., wrecks); the slope, defined in three categories: horizontal (< 30°), sloping (30°-80°), and (sub)vertical (> 80°); the depth; the abundance of animal forests; and the distance from the nearest coast (calculated in QGIS). The substratum type and the slope variability at each site were visually estimated on a scale of 0–3. A score of 0 indicated the absence of a particular substratum or slope category, whereas a score of 3 indicated that the category was highly prevalent at the site. This approach provided a measure of the diversity and complexity of the seafloor's features. Abundance of animal forests was estimated on a scale of 0–3, representing increasing habitat-forming species occurrence from absence (0) to high presence (3), based on the number, size, and density of the main Mediterranean habitat-forming species (i.e., structuring Cnidaria and Porifera). Finally, the putative impact of seafloor litter (entanglement) on animal forests was visually estimated on a 0–3 scale: 0 (absent, no impact), 1 (low impact, < 25% of colonies entangled), 2 (medium impact, 25–50% of colonies entangled), 3 (high impact, > 50% of colonies entangled).

Anthropogenic variables included coastal population density and marine traffic. Coastal population density, derived from population data for the nearest coastal port, was obtained from the Italian National Institute of Statistics (ISTAT) database (2023; https://www.istat.it/classificazione/principali-statistiche-geografiche-sui-comuni/). Marine traffic was derived from vessel-density maps downloaded from the European Marine Observation and Data Network (EMODnet) (https://emodnet.ec.europa.eu/en/human-activities). The maps, in GeoTIFF format, are based on Automatic Identification System (AIS) data and show shipping density in 1 × 1 km grid cells covering all EU waters and some neighbouring areas. Density is expressed as hours per square kilometre per month. The following ship types were considered in the analysis: fishing vessels, sailing vessels, pleasure craft vessels, and passenger vessels. In this work, the mean for 2017–2023 was used. Given the strong correlation between the numbers of sailing and pleasure craft vessels (Pearson's $r = 0.93$), the two variables were aggregated into a single metric, "recreational vessel density", representing the density of recreational maritime traffic. This aggregation was performed to reduce multicollinearity and to provide a more robust indicator of recreational boating pressure.

2.2. Statistical analyses

All statistical analyses were conducted using R (v. 4.2.3; R Core Team, 2023). As the data were non-normally distributed (Shapiro-Wilk normality test, $p < 0.05$), the Kruskal-Wallis test was used to assess differences in litter density across depth classes, macroareas, and litter types. Post hoc pairwise comparisons were performed using the Dunn test.

PERMANOVA based on Euclidean distances was applied to the multivariate dataset, considering all five litter categories simultaneously. This multivariate approach assessed whether the overall litter composition differed among macroareas. Post hoc pairwise comparisons were conducted using the Pillai test.

To investigate the relationship between depth, slope, substratum type, animal forest, entanglement, and the distribution of marine litter, litter was further classified into two macrocategories: general waste (including artificial polymer materials and other) and ALDFG (including lines and ropes, nets, and other fishing-related items).

To visualise the bathymetric distribution of litter occurrences across macroareas, violin plots were used.

Separate linear models were fitted for each litter macrocategory, with the log(x + 1)-transformed litter density as the response variable, to evaluate the relationship with environmental predictors (substratum type and slope). Environmental variables describing substratum type and slope were derived from ROV video analysis estimates and are therefore semi-quantitative, expressed on ordinal scales ranging from 0 (absence) to 3 (high abundance). To avoid assuming linearity among classes, these variables were included in the models as categorical factors, allowing each level to be estimated independently relative to a reference category. The slope model included three predictors (horizontal, sloping, and (sub)vertical), and the substratum model included six types, each scored on a 0–3 scale indicating increasing abundance.

To assess the contribution of different litter macrocategories to entanglement events, the ordinal response variable (ranging from 0 for no entanglement to 3 for high entanglement) was modelled using an ordered logistic regression. The model included litter categories as predictors, as well as animal forest abundance (0–3), which was also treated as a categorical factor. To assess whether animal forest abundance improved model performance, nested ordered logistic regression models were compared using likelihood ratio tests and Akaike's Information Criterion (AIC).

To describe the relationship between marine litter density and both anthropogenic and environmental predictors, a Generalised Additive Model (GAM) was fitted. The model was constructed using the gam() function from the mgcv package in R (Wood, 2017). A Gaussian error distribution with an identity link function was assumed after a $\log(x + 1)$ transformation of the response variables to reduce skewness and improve model assumptions. All predictors were modelled using penalised regression splines (s()), allowing for flexible non-linear relationships between the covariates and the response variable. The basis dimension (k) was increased where diagnostic checks (k-index <1) indicated potential underfitting. Model adequacy was assessed using the gam.check() diagnostic framework, including evaluation of residual patterns and basis dimension sufficiency. By integrating these variables, the study aimed to assess the extent to which human presence and activity contribute to patterns of marine litter accumulation.

3. Results

3.1. Litter abundance, geographic distribution, and composition

Overall, 10,982 litter items were recorded at the surveyed sites (Table 2) across all macroareas, but their distribution was uneven, with significant local variation in litter abundance and composition (Table 2–3). Only 8.6% of the surveyed sites ($n = 59$) were free of litter (Fig. 1).

Average litter abundance was 1.5 ± 0.1 items 100 m^{-2}, with a maximum of 16 items 100 m^{-2}; yet only 1% of sites exhibited an abundance greater than 10 items 100 m^{-2} (Fig. 1).

Significant differences in litter density were observed among the macroareas (Kruskal–Wallis $H = 155.1$, df = 5, $p < 0.001$; Fig. 2A). The Ligurian Sea showed the highest litter abundance (3.2 ± 0.2 items 100 m^{-2}), followed by the Adriatic-Ionian seas (1.3 ± 0.2 items 100 m^{-2}). By contrast, the Sardinian Sea recorded the lowest abundance (0.3 ± 0.1 items 100 m^{-2}).

ALDFG items were the most abundant in the dataset, accounting for 70.8% of the total litter items recorded (Fig. 2B, Table 3). They were predominantly lines and ropes (57.5%), followed by nets (11.1%), with smaller proportions of other fishing-related items (2.2%). Artificial polymer materials accounted for 10.1% of the total litter items identified. In contrast, the category other (including glass/ceramics, metals, and other materials) accounted for 19.1% of the overall litter composition (Fig. 2B).

The composition of litter types varied across the surveyed areas (Fig. 2C). Particularly, ALDFG was the most common litter type in the Ligurian Sea (73.7%) and the Sicily Channel (82.7%). The proportion of artificial polymer materials ranged from 5.2% in the Sicily Channel to 24.1% in the Adriatic-Ionian seas. Finally, other litter types ranged from 12.2% in the Sicily Channel to 30.0% in the Adriatic/Ionian seas (Fig. 2C, 3, Table 3). A significant difference in litter composition among macroareas was detected (PERMANOVA, $p < 0.001$), except for Sardinia, which differed significantly only from the Adriatic/Ionian and Ligurian seas (Pillai's test, $p < 0.001$).

3.2. Bathymetric distribution

Litter was recorded throughout the entire explored depth range, from 40 to 2100 m (Fig. 4). Overall, density decreased with depth, except in the deepest depth class, where a marked increase was recorded (Fig. 5). This was observed at three surveyed sites in the Ligurian Sea: the Penelope and Ulisse seamounts and a site off Sestri Levante, located between 409 and 715 m, where litter density was exceptionally high. Significant differences were observed among the first three depth classes (Kruskal–Wallis, $H = 22.36$, df = 4, $p < 0.01$).

Although the horizontal distribution of litter showed a high density near the coast, litter density did not decline constantly from the coast to the offshore region.

3.3. Relation with explanatory variables

The linear model assessing the relationship between macrolitter density and slope showed the strongest association between ALDFG and sloping or (sub)vertical categories ($p < 0.001$). In contrast, horizontal slopes were significantly associated with general waste ($p < 0.01$), but showed no significant relationship with ALDFG.

For the general waste category, significant differences were observed between hard and soft substrata, with soft bottoms and horizontal slopes accumulating the most non-fishing-related litter ($p < 0.05$). Conversely, rocky substrata showed significantly positive relations with higher ALDFG density across all ranks (1–3) ($p < 0.01$). Bioconstructions and thanatocoenoses were also positively associated with ALDFG density ($p < 0.001$). Mud and detritic substrata had weaker, more variable effects, whereas artificial reef substrata showed no significant association.

Entanglement occurred at 57.2% of explored sites, and 15% of sites had the highest entanglement occurrence (rank 3). The Ligurian and Tyrrhenian seas were the macroareas with the highest occurrence of entanglement events (55–73% of sites), followed by the Sicily Channel (52%). The ordered logistic regression model confirmed that entanglement was more frequent in areas with higher densities of fishing lines, ropes, and especially nets ($p < 0.001$). Artificial polymer materials

Table 2
Sampling effort and litter data per macroarea. LIG = Ligurian Sea, NCT = North-central Tyrrhenian Sea, ST = South Tyrrhenian Sea, SARD = Sardinian Sea, SC = Sicily Channel, ADR/ION = Adriatic-Ionian seas.

Macroarea	no. sites	Surveyed area (m^2)	Surveyed area (%)	Sites with litter (%)	Litter items (no.)	Litter items (%)	Mean density (items 100 m^{-2} ± se)	Max density (items 100 m^{-2})
LIG	156	265,871.6	32.3	94.9	6432	58.6	3.2 ± 0.2	16.1
NCT	132	163,339.5	19.8	89.4	907	8.2	0.7 ± 0.1	4.8
ST	213	215,080.1	26.2	93.9	2156	19.6	1.1 ± 0.1	13.5
SARD	33	34,557.0	4.2	75.8	96	0.9	0.3 ± 0.1	1.6
SC	87	89,343.8	10.9	89.7	814	7.4	1.1 ± 0.2	9.9
ADR/ION	62	54,513.0	6.6	88.7	577	5.2	1.3 ± 0.2	5.7
Total	683	**822,704.9**	–	91.4	**10,982**	–	1.5 ± 0.1	

Table 3
Density of litter (items 100 m^{-2}) categories in each macroarea with indication of mean, median, and maximum values. LIG = Ligurian Sea, NCT = North-central Tyrrhenian Sea, ST = South Tyrrhenian Sea, SARD = Sardinian Sea, SC = Sicily Channel, ADR/ION = Adriatic-Ionian seas.

	LIG	NCT	ST	SARD	SC	ADR/ION
Artificial polymer materials						
mean ± se	0.34 ± 0.09	0.07 ± 0.01	0.13 ± 0.03	0.03 ± 0.01	0.08 ± 0.02	0.28 ± 0.08
median	0.07	0	0	0	0	0.02
max	11.37	0.78	5.00	0.25	1.33	3.38
Other						
mean ± se	0.47 ± 0.04	0.16 ± 0.03	0.29 ± 0.04	0.07 ± 0.03	0.15 ± 0.04	0.37 ± 0.08
median	0.30	0	0.09	0	0	0.09
max	3.38	1.64	5.56	0.75	2.67	3.13
Lines and Ropes						
mean ± se	2.01 ± 0.19	0.29 ± 0.03	0.54 ± 0.04	0.15 ± 0.03	0.73 ± 0.16	0.56 ± 0.11
median	1.29	0.19	0.36	0.10	0.32	0.27
max	13.73	2.50	3.39	0.63	8.74	4.15
Nets						
mean ± se	0.33 ± 0.04	0.12 ± 0.02	0.14 ± 0.02	0.05 ± 0.02	0.13 ± 0.03	0.04 ± 0.01
median	0.15	0.07	0	0	0	0
max	2.58	1.95	1.67	0.38	2.00	0.40
Other fishing-related items						
mean ± se	0.07 ± 0.01	0.03 ± 0.01	0.02 ± 0.00	0.02 ± 0.01	0.05 ± 0.02	0.03 ± 0.01
median	0	0	0	0	0	0
max	1.13	1.25	0.44	0.38	1.62	0.72

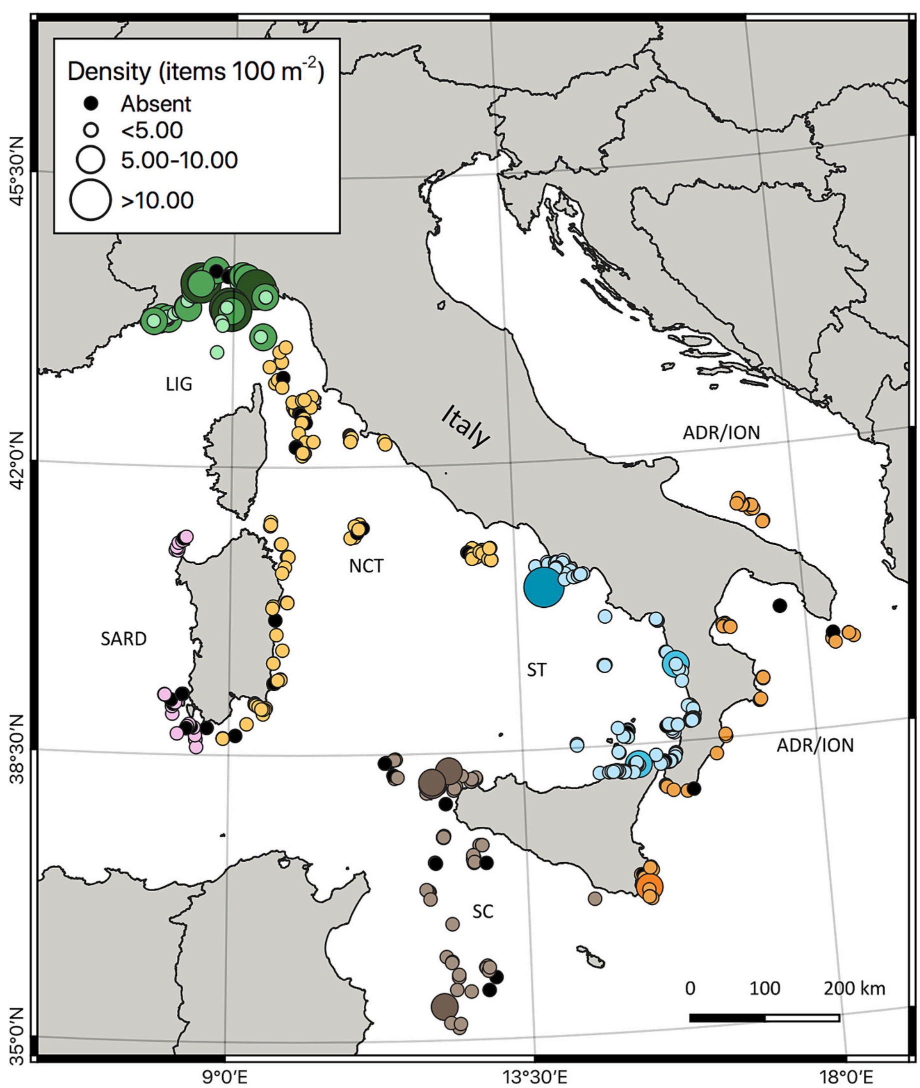

Fig. 1. Distribution map of the investigated sites and litter abundance. LIG = Ligurian Sea (green dots), NCT = North-central Tyrrhenian Sea (yellow dots), ST = South Tyrrhenian Sea (blue dots), SC = Sicily Channel (brown dots), SARD = Sardinian Sea (pink dots), ADR/ION = Adriatic-Ionian seas (orange dots). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

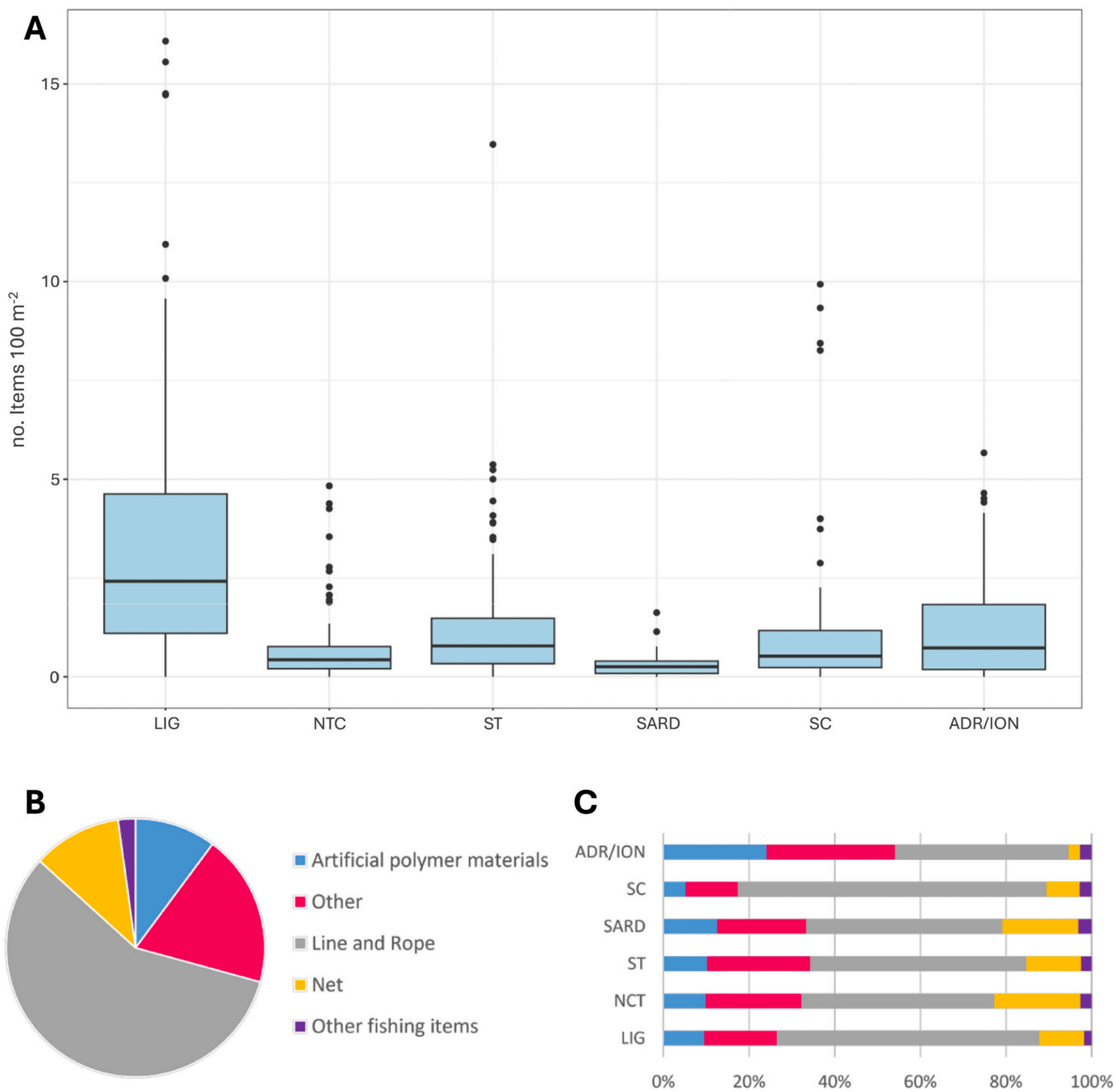

Fig. 2. Litter density and composition of litter in the macroareas. A) Box-plot of litter density in each macroarea: boxes indicate the first and third quartiles; bold lines indicate the median value; lines indicate the range between the minimum and maximum values; and dots indicate outliers. B) Pie-chart of litter categories; C) Percentage frequency of litter categories in each macroarea. LIG = Ligurian Sea, NCT = North-central Tyrrhenian Sea, ST = South Tyrrhenian Sea, SARD = Sardinian Sea, SC = Sicily Channel, ADR/ION = Adriatic-Ionian seas.

showed a weak positive effect ($p < 0.05$), whereas other litter categories were not significantly related to entanglement. Other fishing-related items showed a significant negative association ($p < 0.001$). The probability of entanglement increased significantly with increasing animal forest abundance. All forest abundance ranks (1–3) showed a statistically significant positive effect compared to the absence of forests ($p < 0.001$). Including animal forest abundance as an explanatory variable significantly improved model fit ($\Delta AIC = 255$; likelihood ratio test, $p < 0.001$).

The GAM outputs indicated that depth ($p < 0.001$) and distance from the coast ($p < 0.001$) exerted significant non-linear effects on general waste density. Recreational vessel density also showed a significant non-linear relationship with litter abundance ($p < 0.01$). In contrast, passenger vessel density was not significantly associated with the response variable, and fishing vessel density did not show a significant effect. In the model restricted to ALDFG, significant non-linear effects on litter density were detected exclusively for depth ($p < 0.001$), population density ($p < 0.001$), distance from the coast ($p < 0.001$), and recreational vessel density ($p < 0.001$). Passenger vessel density and fishing vessel density were not significantly associated with ALDFG abundance.

3.4. *MSFD seafloor litter threshold value*

Considering data up to 200 m depth ($n = 515$, 75.4% of sites), 87% of sites exceeded the EU threshold (Table 4). The regions with the highest numbers of sites exceeding TV were the southern Tyrrhenian Sea (37%), the Ligurian Sea (23%), and the northern Tyrrhenian Sea (19%).

4. Discussion

4.1. *Geographic and bathymetric distribution*

This study provided comprehensive data on seafloor macrolitter, enabling a large-scale assessment of its quantity, composition, spatial distribution, and impacts on benthic communities in the mesophotic and deep waters of the Italian seas. Consistent with previous research in various seas and oceans worldwide (e.g., Galgani et al., 1996, 2000; Bergmann and Klages, 2012; Schlining et al., 2013; Shimanaga and Yanagi, 2016; Chiba et al., 2018; and references therein), seafloor macrolitter was observed across all regions, covering extensive geographical and bathymetric ranges. Litter items were recorded at

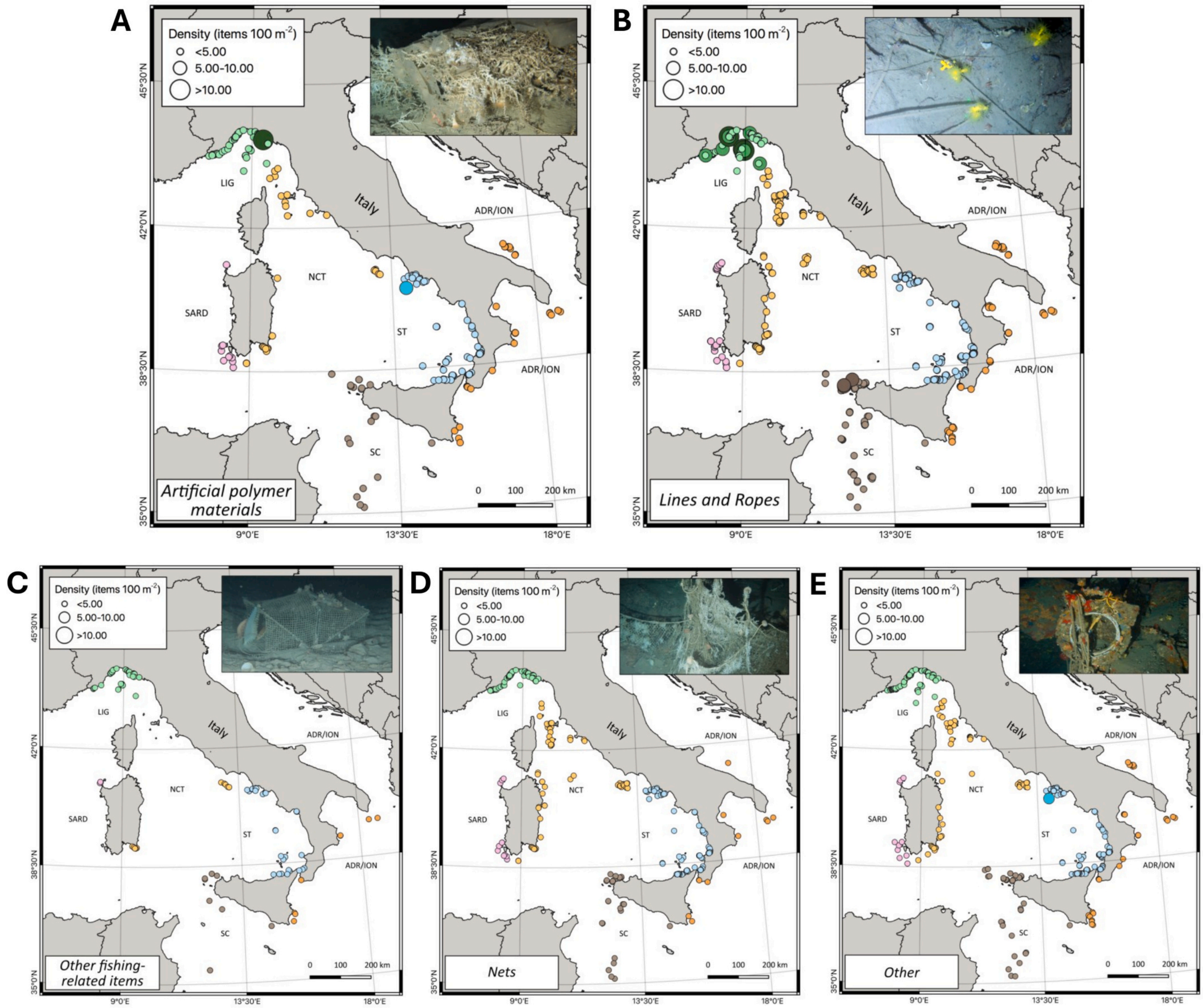

Fig. 3. Distribution maps of the investigated sites and the recorded litter abundance (items 100 m-^{2}) in each site for the five considered categories: A) artificial polymer materials (excluding ALDFG); B) other; C) lines and ropes; D) nets; E) other fishing-related items. For the colour legend, see Fig. 1. LIG = Ligurian Sea, NCT = North-central Tyrrhenian Sea, ST = South Tyrrhenian Sea, SARD = Sardinian Sea, SC = Sicily Channel, ADR/ION = Adriatic-Ionian seas.

91.4% of surveyed sites in coastal and offshore environments, including continental shelves, reef habitats, canyons, and seamounts. This confirms their widespread presence, although with notable spatial variability among macroareas (Galgani et al., 2015).

The highest densities were detected in the macroareas of the Ligurian Sea, the Adriatic/Ionian seas, the South Tyrrhenian Sea, and the Sicily Channel—areas already recognised for high litter volumes, particularly ALDFG (Bo et al., 2014; Angiolillo et al., 2015; Ferrigno et al., 2018, 2021; Angiolillo and Fortibuoni, 2020; Crocetta et al., 2020; Enrichetti et al., 2020). These regions are among the most urbanised along the Italian coast, characterised by densely populated cities, intensive coastal use, significant maritime traffic, and traditional shipping and fishing activities, including artisanal and recreational fisheries (e.g., Cattaneo-Vietti et al., 2010; Ferrigno et al., 2018; Enrichetti et al., 2019). Conversely, the Sardinian continental shelf displayed lower macrolitter levels, indicating less impact in that macroarea. This discrepancy might partly be due to differences in sampling effort, as the Adriatic/Ionian and Sardinian macroareas accounted for only 6.6% and 4.2% of the total explored area, respectively; however, it may also reflect variations in seafloor geomorphology and human impacts. The Adriatic Sea, for example, features shallow continental shelves and sandy-muddy seabeds, with sporadic small to medium-sized reefs in the north (Melli et al., 2017) and along the southern Apulian shelf (Savini and Corselli, 2010; Bargain et al., 2017; Ingrosso et al., 2018), where litter tends to accumulate. Conversely, Sardinia has a lower population density and less fishing activity compared to other Italian regions, leading to lower observed litter density levels (Angiolillo et al., 2015, 2023a, 2024; Cau et al., 2017).

Litter density also varied with depth, generally decreasing as depth increased – a pattern consistent with previous observations (e.g., Watters et al., 2010; Haarr et al., 2022; Zhu et al., 2024) - but showing high peaks in deep environments (Angiolillo et al., 2021; Pierdomenico et al., 2019; Hanke et al., 2025b). The elevated densities recorded at the three Ligurian sites, mainly related to ALDFG, were possibly attributable to intense fishing pressure from commercial and recreational fisheries, resulting in accumulation points for litter (Cattaneo-Vietti et al., 2010; Ferrigno et al., 2018; Enrichetti et al., 2019; Angiolillo et al., 2015, 2021, 2023a).

In the deep Mediterranean Sea, Angiolillo et al. (2021) demonstrated that litter density increases with depth, depending on litter type,

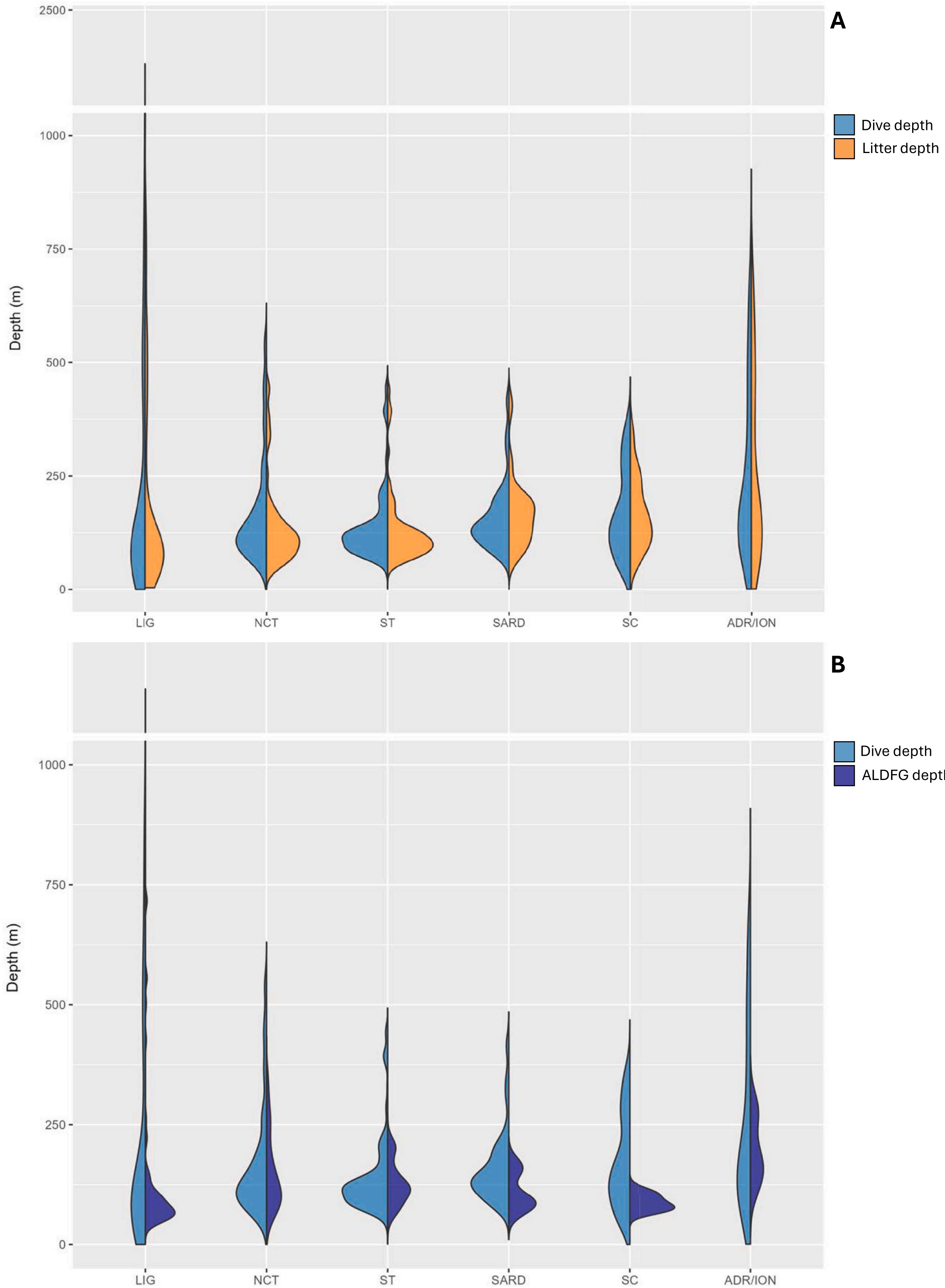

Fig. 4. Bathymetric distribution of litter items. The left side of the violins (light blue) shows the bathymetric range explored for each macroarea, whereas the right side shows the bathymetric range where A) total litter and B) ALDFG were found. LIG = Ligurian Sea, NCT = North-central Tyrrhenian Sea, ST = South Tyrrhenian Sea, SARD = Sardinian Sea, SC = Sicily Channel, ADR/ION = Adriatic-Ionian seas. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

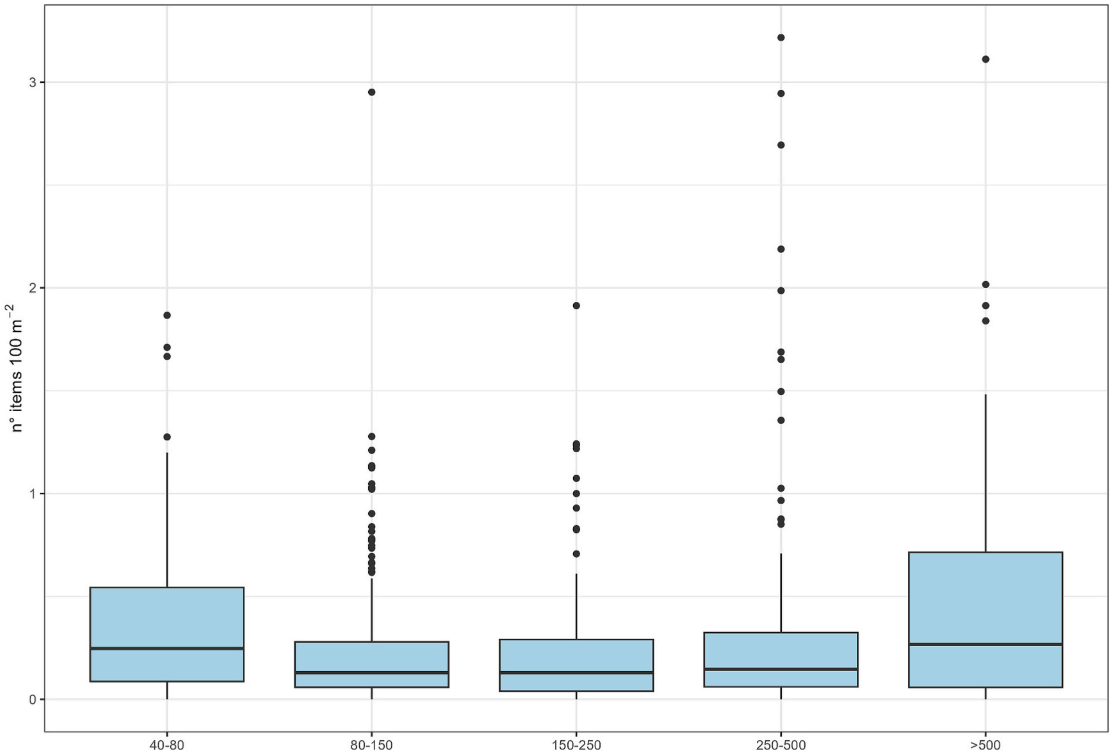

Fig. 5. Box-plot of litter density related to depth: boxes indicate the first and third quartiles; bold lines indicate the median value; lines indicate the range between the minimum and maximum values; and dots indicate outliers.

Table 4
Number (no.) and percentage (%) of sites in each macroarea within 200 m depth with litter density below or above the EU threshold value (TV). LIG = Ligurian Sea, NCT = North-central Tyrrhenian Sea, ST = South Tyrrhenian Sea, SARD = Sardinian Sea, SC = Sicily Channel, ADR/ION = Adriatic-Ionian seas.

Macroarea	no. sites d < TV	no. sites d > TV	% sites d > TV
LIG	3	102	97%
NCT	17	85	83%
ST	16	166	91%
SARD	11	17	61%
SC	8	54	87%
ADR/ION	10	26	72%
Tot	**65**	**450**	**87**

TV = 1000 items km^{-2}.

substratum, and slope. Their results indicated that ALDFG are easily entangled on the summits of deep seamounts, spurs, outcrops and are particularly prevalent in areas historically affected by small-scale fisheries, characterised by a complex topography (Angiolillo et al., 2021; Bo et al., 2020, 2023).

Conversely, plastic, glass, and other urban waste are the most common litter types in bathyal and abyssal environments across large, flat areas. In the Mediterranean, deep-sea litter accumulation points, mainly composed of general waste, are typically located at the bases of canyons and trenches, such as the Messina Strait (Pierdomenico et al., 2019), the Monaco Canyon (Angiolillo et al., 2021), the Beaulieu Canyon (Angiolillo pers. com.), and the Calypso Deep (Hanke et al., 2025b), where exceptionally high values have been recorded. Submarine canyons act as major pathways for the transfer of litter from shallow coastal waters to the deeper seabed, where it tends to accumulate in large quantities. Nonetheless, because they represent peculiar depositional environments, they are unlikely to provide a representative picture of the overall litter distribution (particularly for plastics) across the broader seabed (Pham et al., 2014; Galgani et al., 2019).

4.2. Seafloor litter abundance

Abundance values in this study ranged from 0 to 16.1 items per 100 m^2, with a mean of 1.5 ± 0.1 items per 100 m^2. These litter densities are consistent with previous ROV-based investigations in the Mediterranean Sea (e.g., Mordecai et al., 2011; Tubau et al., 2015; Dominguez-Carrió et al., 2020; Kouvara et al., 2025). Recent large-scale surveys have examined depths up to approximately 2000 m (see Table 5). When converted to square kilometres, the recorded density (15,000 ± 110 items km^{-2}) is estimated to be one to two orders of magnitude higher than figures reported for the Azores Archipelago in the North Atlantic Ocean (113 ± 310 items km^{-2}; Duncan et al., 2023) and the eastern Red Sea (4069 ± 1188 items km^{-2}; Martynova et al., 2024). In contrast, our estimates are similar to those obtained during national MSFD monitoring in shallower Italian waters, which record 58,000 ± 360 items km^{-2} (Angiolillo et al., 2023a).

Expressing densities per square kilometre facilitates broad comparisons and highlights the magnitude of deep-sea pollution. However, this conversion can introduce extrapolation bias, as ROV transects in this study typically span only a few hundred metres, usually on rocky habitats, and upscaling to km^2 may inflate variability. Consequently, comparisons among seafloor litter studies remain challenging. To minimise inconsistencies, the present study compares results primarily with studies employing similar methodologies, although caution is still necessary when interpreting cross-study differences.

4.3. Seafloor litter composition and effect on benthic habitat

ALDFG constituted the predominant category of deep-sea litter, accounting for approximately 70.8% of the total items, primarily lines and ropes. The structural complexity of rocky substrates in the study area facilitates the entanglement of ALDFG, especially lines and ropes—a pattern well documented in the Mediterranean Sea, particularly in rugged regions (Bo et al., 2014; Tubau et al., 2015; Angiolillo, 2019; Dominguez-Carrió et al., 2020; Angiolillo and Fortibuoni, 2020).

Table 5
Metadata of several recent large-scale studies carried out in mesophotic and deep waters.

Area	Years	Dives (no.)	depth range (m)	litter items (no.)	Abundance (items km^{-2} ± se)	Type of litter (%)	References
Japanese archipelago (North Pacific)	1983–2014	5010	1092–5977, 10,898*	3425	17 to 335**	–	Chiba et al., 2018
Azores (North Atlantic)	2006–2020	351	213–2387	1799	113 ± 310	83 ALDFG	Ducan et al., 2023
Italian seas (Mediterranean)	2015–2019	416	14–199	4316	54,800 ± 3600	86 ALDFG	Angiolillo et al., 2023b
Eastern Red Sea	2022	84	93–2415	755	4069 ± 1188	46 plastic	Martynova et al., 2024
Italian seas (Mediterranean)	2007–2023	745	40–2129	10,982	15,000 ± 1100	70.8 ALDFG	This study

* The maximum depth at which litter items were detected on the seafloor of the Mariana Trench.
** Density refers only to the data subset from the SHINKAI 6500 dives between 2004 and 2014.

Adverse weather conditions, tracking system failures, snagging on submerged features, and improper fishing methods—including illegal use of ingegno or temporary moorings—can lead to both intentional and unintentional loss or discarding of fishing gear (Bo et al., 2014; Cattaneo-Vietti et al., 2017; Richardson et al., 2018). Illegal gear dumping, involving nets, steel cable bundles, longlines, and fish aggregating devices, also contributes to the problem, often occurring when onshore disposal is unfeasible or too costly, a situation worsened by the lack of port reception infrastructure (Deidun et al., 2015; Gilman, 2015).

The linear model revealed a strong association between ALDFG presence and rocky, sloping environments. Conversely, sandy or muddy horizontal seabed areas harboured higher proportions of artificial polymer materials and other litter types. These findings suggest that slope, topography, and physical factors—such as wind and currents—as well as biological influences, such as ingestion and fouling, significantly shape litter distribution on the seafloor. This pattern aligns with previous observations (Bo et al., 2014, 2020, 2023; Angiolillo et al., 2015, 2021; Fakiris et al., 2022; Melli et al., 2017; Hanke et al., 2025b).

Due to their buoyancy, single-use plastics may be transported over long distances by ocean currents before settling on the deep seafloor (Chiba et al., 2018). In contrast, ALDFG tends to accumulate in areas of intense artisanal fishing activity, typically in rocky or reef habitats, thereby contributing significantly to ecological impacts in these zones. Artisanal and recreational fishing activities are difficult to track because small boats (< 15 m) often lack AIS equipment. Data are limited to larger, professional vessels (> 12 tons) that generally avoid complex grounds during trawling or seine fisheries. Few studies have explored the connection between artisanal or recreational fishing intensity, gear loss, ALDFG density, entanglement, bycatch, and overall seabed litter impact (e.g., Enrichetti et al., 2019; Betti et al., 2020; Angiolillo and Fortibuoni, 2020). Natural features such as shelf rocky outcrops, coralligenous formations, CWC forests, thanatocoenoses, and seamounts act as sinks for litter, especially ALDFG. Human activity likely amplifies this accumulation, which explains the high concentrations observed in this study (Angiolillo et al., 2015, 2023a; Melli et al., 2017; Consoli et al., 2018, 2019a). Consequently, systematic monitoring of small-scale and recreational fisheries—advocated by several researchers (Bo et al., 2020; Angiolillo and Fortibuoni, 2020)—is necessary to quantify their contribution and develop effective mitigation strategies (Bo et al., 2020).

The significant input of marine litter, particularly ALDFG, exerts considerable pressure on mesophotic and deep benthic habitats in some areas of the Italian seas (Angiolillo and Fortibuoni, 2020; Bo et al., 2014; Enrichetti et al., 2020). It promotes entanglement of habitat-forming and large species, causing damage as widely documented in the literature (Bruemmer et al., 2023; Cattaneo-Vietti et al., 2010; Consoli et al., 2018; Ferrigno et al., 2018, 2021). Entanglement was observed in 57.2% of cases, with 15% showing severe impacts on benthic communities. The model indicated that rocky, biogenic, or artificial substrates, as well as animal forests, are associated with a higher likelihood of entanglement. This evidence underscores the risks posed by litter, particularly ALDFG, to marine ecosystems. Although further research is needed to quantify biological effects, immediate measures are essential to prevent further damage (Chiba et al., 2018). Variability in entanglement rates across species and life stages remains poorly understood, hampering comprehensive assessments of vulnerability and interaction frequency. Future studies should establish baseline data on litter abundance, ecological impacts, and effects on benthic habitats, especially given the spatial heterogeneity and limited current knowledge in Mediterranean systems.

4.4. Constraints of the study

ROV video footage proved to be an effective method for studying litter in mesophotic and bathyal environments, offering non-invasive data collection, broad geographic applicability, suitability for complex habitat surveys, georeferenced data, no bathymetric constraints, and generally good detectability of large items. The effectiveness of this method has been demonstrated in previous studies (e.g., Tubau et al., 2015; Canals et al., 2020, and references therein), including those targeting marine organisms (e.g., Bo et al., 2020; Toma et al., 2022, 2024).

Some limitations occur with buried or unidentifiable items, as close inspection or retrieval was often not feasible. Additionally, under low-visibility conditions, the ROV could detect litter only at very close range. In this context, video resolution and illumination strongly influence data quality, as do operational variables such as ROV speed, depth above the seafloor, and camera angle (Bell et al., 2023). The opportunistic nature of the dataset introduces additional sources of variability. The surveys span multiple years, projects, and different ROV systems and configurations. Variations in camera resolution, altitude, field-of-view width, speed, and illumination conditions, as well as estimates of surveyed area, could affect litter detectability and thereby contribute to the observed variability in litter density. Nonetheless, the analytical and standardised approach provided valuable large-scale insights into seafloor litter distribution and impacts, although the non-systematic sampling design remains an inherent limitation.

Despite this challenge, litter was detected at 91% of sites, with nearly 11,000 items recorded, most of which ALDFG. As a non-destructive technique, ROVs and other deep-sea vehicles could be valuable tools for monitoring seafloor litter and assessing its effects on deep-sea organisms (Chiba et al., 2018; Hanke et al., 2025a, 2025b). ROV imaging has enabled the characterisation of litter distribution across large spatial scales and at great depths over the past few decades. However, because comprehensive surveys are unfeasible due to high operational costs and time-consuming analyses, monitoring efforts should prioritise ecologically valuable, rare, or vulnerable ecosystems, including deep-sea coral habitats, chemosynthetic communities, and areas highly exposed to litter risk (Chiba et al., 2018). In this context, long-term, government-supported monitoring programmes (e.g., MSFD) are essential for collecting multi-decadal datasets and assessing temporal trends. In this regard, this study provides baseline observations of litter distribution in mesophotic and deep waters, which can serve as a reference for further monitoring of areas (see Table 6).

Table 6
List of areas highly exposed to litter risk (ALDFG ≥1 items 100 m^{-2}), and areas monitored under Italian MSFD.

Macroarea	Area	no. sites	Mean ALDFG abundance (items 100 m^{-2})	Vulnerability
LIG	Sanremo	39	1.8	highly exposed to fishing-related litter risk
LIG	Imperia	12	1.9	highly exposed to fishing-related litter risk
LIG	Savona	35	2.8	highly exposed to fishing-related litter risk
LIG	Genova	15	1.2	highly exposed to fishing-related litter risk
LIG	Portofino	18	1.8	highly exposed to fishing-related litter risk
LIG	Sestri Levante	13	2.3	highly exposed to fishing-related litter risk
LIG	La Spezia	7	2.8	highly exposed to fishing-related litter risk
LIG	Ulisse Seamount	6	6.6	highly exposed to fishing-related litter risk
LIG	Santa Lucia Seamount	2	4.1	highly exposed to fishing-related litter risk
LIG	Penelope Seamount	3	10.0	highly exposed to fishing-related litter risk
SARD	Sardinia South East	20	1.1	highly exposed to fishing-related litter risk
ST	Gulf of Naples	34	1.1	highly exposed to fishing-related litter risk
ST	Gulf of Salerno	10	1.2	highly exposed to fishing-related litter risk
ST	Acciaroli	1	1.5	highly exposed to fishing-related litter risk
ST	Maratea	7	1.5	highly exposed to fishing-related litter risk
SC	Offhore San Vito	18	2.2	highly exposed to fishing-related litter risk
ADR/ION	Messina Strait	4	1.0	highly exposed to fishing-related litter risk
ADR/ION	Siracusa	14	1.3	highly exposed to fishing-related litter risk
NCT	Corsica Channel	4	0.3	CWC forests - MSFD monitoring activities
ST	Pontine Archipelago	20	0.5	CWC forests - MSFD monitoring activities
ST	Dohrn Canyon	11	0.5	CWC forests - MSFD monitoring activities
ADR/ION	Bari Canyon	11	0.5	CWC forests - MSFD monitoring activities
ADR/ION	Santa Maria di Leuca	8	0.4	CWC forests - MSFD monitoring activities
SC	Linosa Island	6	0.5	CWC forests - MSFD monitoring activities

4.5. Future directions

The widespread presence of litter and its extensive distribution across the deep Mediterranean seafloor emphasise the need for coordinated, basin-wide measures to reduce pollution inputs effectively (Hanke et al., 2025a, 2025b). Current policies focus on mitigating the environmental impact of marine litter through ongoing initiatives, including the MSFD, the EU Plastics Strategy, the EU Zero Pollution Action Plan, and regional programs such as the Mediterranean Action Plan. Building on MSFD data, Italy enacted the "Salvamare" Law (Law No. 60/2022), which introduced targeted measures to prevent riverine waste from entering the sea and to carry out cleanup actions both at sea and in rivers. Moreover, Directive (EU) 2019/883 institutionalised "fishing for litter" by establishing a mandatory framework requiring that passively fished waste be landed and delivered to port reception facilities without disincentive fees, thereby embedding marine litter collection as an obligatory component of routine fishing activities (Mannaart and Bentley, 2022). However, although legal and management frameworks to address marine litter exist, their effectiveness is limited by poor implementation. Public awareness remains insufficient, further complicating the issue. Additionally, port waste reception facilities need substantial improvements, and stricter regulations are required for the disposal of litter.

Public education through targeted campaigns, as emphasised by Kouvara et al. (2025), is equally critical. These shortcomings must be viewed within a broader historical context: for decades, the marine environment, especially the deep sea, was neglected and often used as a dumping site—a practice with long-lasting ecological consequences that are now becoming apparent (Angiolillo, 2019; Hanke et al., 2025a, 2025b). The discovery of widespread artificial polymer materials and ALDFG at extreme depths underscores the direct link between human activities and remote deep-sea environments. Although deep-sea ecosystems receive less attention than coastal areas, they provide vital services to humanity, including provisioning (genetic and bioprospecting resources), regulating (nutrient cycling), and cultural (educational and scientific knowledge) services (Danovaro et al., 2010; Ramírez-Llodra et al., 2011). Once litter is deposited in the deep ocean, it can persist for hundreds to thousands of years due to the absence of UV radiation and minimal hydrodynamic disturbance (Barnes et al., 2009).

Despite efforts by volunteer groups, NGOs, and local and national authorities worldwide—including beach clean-ups, at-sea removals, and public awareness campaigns (OSPAR, 2010; Konecny et al., 2018; Consoli et al., 2019a, 2019b)—the sheer scale of global plastic production and waste remains so vast that large-scale removal efforts are practically impossible, making ocean cleanup an unattainable goal. To protect deep-sea ecosystems from growing plastic pollution and ensure the continuity of their vital services, scientists must provide strong scientific evidence to guide international management strategies. Ultimately, reducing plastic production and preventing its entry into coastal and marine environments are the only sustainable, long-term solutions to mitigate deep-sea plastic pollution (Chiba et al., 2018).

5. Conclusions

This study offers the first comprehensive overview of seafloor marine litter across various regions of the Italian mesophotic and bathyal seas, based on 18 years of ROV investigations. It highlights that ALDFG is among the main sources impacting rocky circalittoral and bathyal assemblages in Italian waters. Overall, our findings reinforce the urgent need for targeted measures to manage marine pollution and cut litter inputs into the environment.

Future research should expand the study area, especially in high-exposure zones such as fishing grounds, litter accumulation sites, and vulnerable habitats, or within long-term monitoring efforts, to gain a more detailed understanding of the spatial distribution of litter in the Mediterranean Sea. The risks posed by plastic pollution to marine life

(Bucci et al., 2020; Mehinto et al., 2022) further emphasise the importance of mapping its spatial extent to better characterise organismal exposure at large scales. Despite the dataset's opportunistic nature, the analytical and standardised approach used here enabled us to derive valuable insights into geographic patterns, sources, and potential human drivers of seafloor litter. Additionally, data up to 200 m indicated that 87% of surveyed sites exceeded the MSFD threshold for marine litter on the seafloor, measured as litter density. Although the dataset is not derived from dedicated monitoring protocols and is biased towards complex environments, it reveals critical conditions in certain Italian areas concerning this issue. While such comparisons are not entirely equivalent and may overestimate environmental degradation, these results provide valuable baseline information to help fill existing methodological gaps in assessing GES in accordance with the requirements of the GES Decision (EU) 2017/848. The adoption of international protocols for marine litter data collection and sharing (e.g., MSFD Technical Group on Marine Litter, 2013, MSFD Technical Group on Marine Litter, 2023), alongside harmonised observation strategies, is highly recommended. Standardised procedures for long-term monitoring would ensure consistent, comparable datasets, advancing scientific understanding of seafloor litter through common item lists (e.g., the MSFD Joint List of litter categories). Incorporating marine litter as a routine variable in long-term benthic biodiversity monitoring programmes should be prioritised to improve data collection and assess the effectiveness of measures implemented to combat marine pollution. Furthermore, evaluating the impacts of litter on marine organisms, including the likelihood of entanglement (fishing effort vs. entanglement), bycatch patterns, and severity of impacts (epibiont coverage, necrosis, mortality, etc.), is essential to fully understand the ecological consequences of seafloor pollution.

CRediT authorship contribution statement

M. Angiolillo: Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **B. Di Lorenzo:** Writing – review & editing, Methodology, Formal analysis, Data curation. **M. Bo:** Writing – review & editing, Investigation, Funding acquisition. **T. Fortibuoni:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **S. Canese:** Writing – review & editing, Investigation, Funding acquisition. **Al Cau:** Writing – review & editing, Investigation, Funding acquisition. **G. Bavestrello:** Writing – review & editing, Funding acquisition. **L. Tunesi:** Writing – review & editing, Investigation, Funding acquisition. **M. Toma:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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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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Data availability

Data will be made available on request.

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