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Linking marine litter from land sources to its spatial distribution on fishing grounds in the NW Mediterranean Sea

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A R T I C L E I N F O

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A B S T R A C T

Marine litter (ML), predominantly originating from land, tends to accumulate on the seabed, where it is often caught unintentionally by bottom trawlers. This study aims to characterize the benthic ML on NW Mediterranean fishing grounds and examine the relationship between land-based sources and the ML spatial distribution. Marine litter was collected onboard commercial bottom trawlers operating along the Catalan margin. Plastic was the most abundant fraction of litter, accounting for up to 63% of the total weight. The key factors influencing the spatial distribution of ML included sampling area, proximity to river mouths, and distance to submarine outfalls. The influence of the fishing effort on the spatial distribution of ML was also analyzed, but no significant correlation was identified. Higher ML concentrations were found in front of Barcelona (up to 201.94 kg km^2), while lower amounts were observed in northern and southern boundaries of the study area. The results emphasize the need for better land waste management strategies to reduce litter accumulation in fishing grounds.

1. Introduction

The ocean is undergoing a planetary crisis facing multiple threats, with marine litter (ML) pollution being one of its most pressing concerns (Mæland and Staupe-Delgado, 2020). This global and transboundary problem has negative effects on all marine ecosystems and affects the population living along the coasts (Bergmann et al., 2015; Mæland and Staupe-Delgado, 2020). Marine litter is globally distributed throughout the marine environment including sea surface, water column and seafloor (Soto-Navarro et al., 2020). Among these, benthic ML has a major negative ecological and economic effect and causes direct and indirect impacts on marine ecosystem services (Coe and Rogers, 1997; McIlgorm et al., 2011). For instance, litter on the seafloor can alter the benthic habitat entangling animals interfering with their ability to move (Angiolillo and Fortibuoni, 2020; Ramirez-Llodra et al., 2011), while its ingestion can cause physical damage, including smothering and starvation (Consoli et al., 2018). Moreover, the chemical additives that plastic items may contain can potentially bioaccumulate and/or be biomagnified through the food web (Bekele et al., 2019; Sala et al., 2022). Marine litter may also cause socio-economic impacts, such as risks to vessel safety, reduced selectivity and damage to fishing gear, and economic losses due to a decline in tourism (Bergmann et al., 2015; Eryas et al., 2014; McIlgorm et al., 2011).

Despite its global scope, ML is not homogenously distributed and some areas are more affected than others. In the Mediterranean Sea, being a semi-enclosed basin with high urban and industrial concentrations along its shores, the ML problem is particularly severe. The high anthropogenic pressure to which this sea is subjected has led to substantial benthic litter accumulation, reaching densities as high as 393 kg km^2 and 316 items km^2 (Galimany et al., 2019; Spedicato et al., 2019), with the detrimental effects these pollution levels can cause to economically important activities in the region such as tourism and fishing (Aretoulaki et al., 2021).

Addressing the ML problem requires globally coordinated efforts to reduce pollution and improve waste management strategies to mitigate its long-term impacts on marine ecosystems and global economies. Several strategies have been proposed to tackle this issue, including prevention, monitoring, cleaning, and combinations of these approaches (Bellou et al., 2021). Of these, the opportunity offered by bottom trawlers to remove ML from fishing grounds has led to the development

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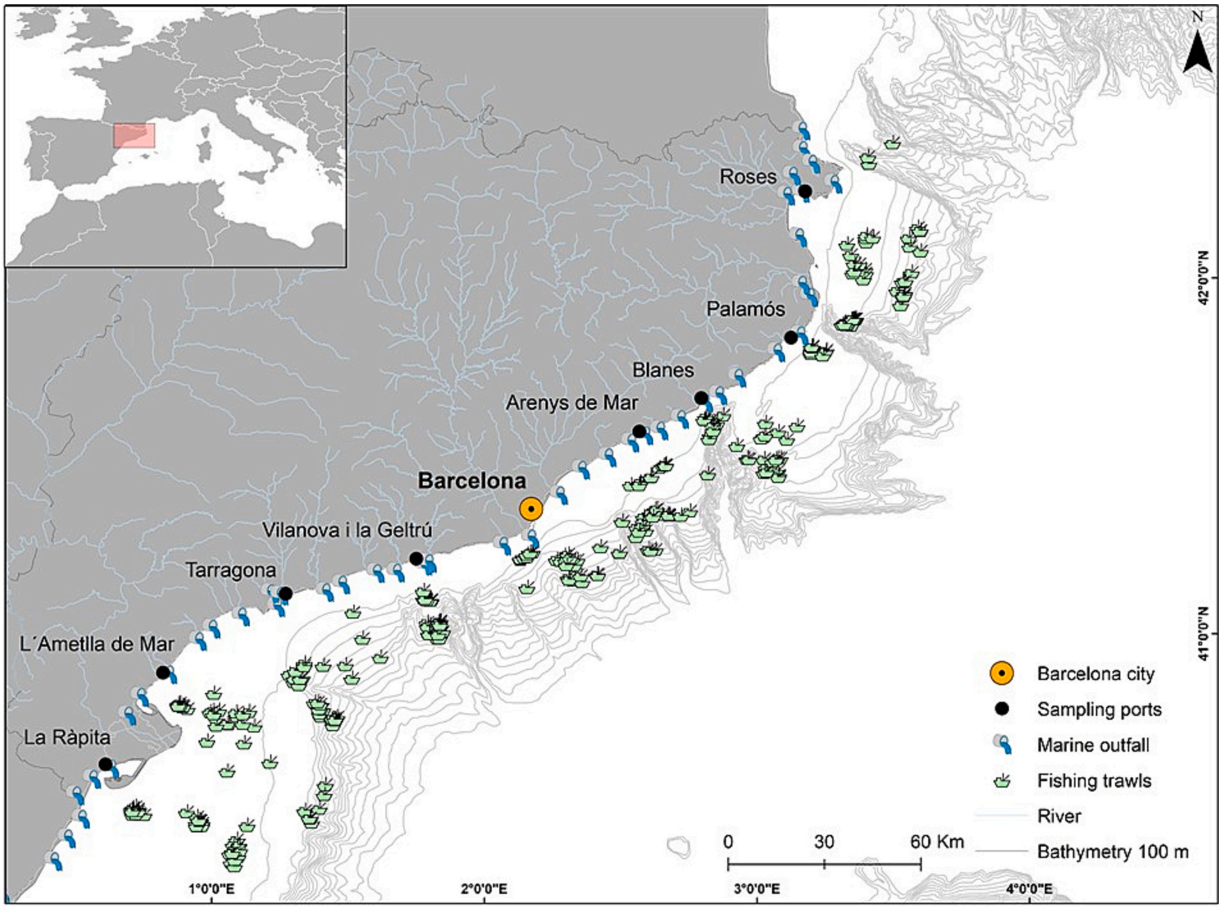

Fig. 1. Map plotting the studied area (Catalan coast) with black dots indicating fishing ports along the coast and an orange circle indicating the city of Barcelona, the main city in the study area (>1.500.000 inhabitants). The middle points of each sampled haul are represented by green boats. Submarine outfalls and river mouths along the coast are shown. Bathymetric isolines show changes every 100 m depth from 0 to 1000 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of Fishing for Litter (FFL) strategies, which consist in returning to land the benthic litter accidentally caught in the fishing nets by bottom trawlers (KIMO, 2015; Ronchi et al., 2019). Enhancing FFL strategies could help remove great quantities of benthic waste which, otherwise, would remain unextracted (KIMO, 2015). As an example, a recent study estimated that the bottom trawl fleet of the Catalan coast (NW Mediterranean Sea) could potentially remove 237 ± 36 t of ML yearly (Balcells et al., 2023). However, since ML reaches the sea through different sources, a multifaceted approach is needed to reduce it, including improved waste management practices on land (Rangel-Buitrago et al., 2023).

Marine litter includes a broad variety of materials, from plastics, to metal, textile and medical waste, among others (UNEP, 2009). Regardless of the type, ML can originate from either marine or terrestrial sources and the best management strategies should be implemented at each source. Marine-based sources include commercial and tourist maritime transport, fishing vessels, recreational boats and offshore facilities, including aquaculture farms (Galgani et al., 2020; García-Rivera et al., 2017; Ramirez-Llodra et al., 2013). On the other hand, land-based sources encompass river discharge, urban and industrialized areas, legal and illegal dumpsites near the coast, and submarine outfalls from wastewater treatment plants (Erüz et al., 2022; Tubau et al., 2015). Nevertheless, the amount of ML from each source is not equal and most of the benthic ML appears to be of terrestrial origin, having reached the ocean through wind transport and river runoff (Tubau et al., 2015). In addition, the composition and quantity of ML varies depending on several factors, such as location, depth, weather events, and environmental conditions (Balcells et al., 2023; Soto-Navarro et al., 2020). Consequently, local studies on ML are essential to inform competent authorities and develop tailored and effective solutions that could be applied on a global scale to tackle the problem (Loizidou et al., 2021; Savelli et al., 2017).

In recent years, modeling studies on ML distribution in the Mediterranean Sea have increased significantly. Most of these studies have focused on floating objects and particles (Compa et al., 2019; Mansui et al., 2015; Soto-Navarro et al., 2020), despite the fact that a large portion of the litter that enters the marine environment eventually settles on the seafloor (Canals et al., 2021; Tubau et al., 2015). In this context, the use of fisheries monitoring programs to track and characterize benthic ML collected by bottom trawlers can provide valuable information on the accumulation and distribution of litter in benthic marine habitats, where it poses significant ecological risks. The objectives of this study are to characterize seafloor ML in northwestern Mediterranean fishing grounds and to identify which land-based sources contribute significantly to predicting its distribution. Additionally, the role of bottom trawlers in the removal of ML is evaluated to assess their potential impact on the spatial distribution of benthic litter. This approach aims to provide a clearer understanding of the connection between land-based pollution sources, trawling activities, and the accumulation of ML on the seafloor.

Table 1
Categorization and description of marine litter.

Category	Description
Metal	Metallic-made items or pieces, i.e. cans, lids
Plastic	Plastic-made objects or pieces, i.e. bags, containers
Rubber	Rubber-made objects or pieces, i.e. balloons, tires
Textiles	Fabric-made clothes or pieces
Wood	Wood-made objects and pieces, i.e. corks, boxes
Other waste	All other marine litter objects and pieces that do not fit in the specific categories, i.e. batteries, glass

2. Materials and methods

2.1. Study site

This study was carried out along the Catalan coast (NW Mediterranean Sea), throughout its 580 km of coastline (Fig. 1). Following Blanco et al. (2023), nine ports were selected on the basis of their commercial importance in Catalonia's bottom trawl fishery. From north to south the ports were Roses, Palamós, Blanes, Arenys de Mar, Barcelona, Vilanova i la Geltrú, Tarragona, l'Ametlla de Mar and La Ràpita. These last two ports include the shallowest depth strata of them all due to the influence of the delta at the mouth of the Ebre River.

2.2. Sampling and marine litter characterization

2.2.1. Sampling

Data were collected onboard registered fishing vessels from the Catalan trawling fleet from November 2018 to December 2022. In summary, three depth strata were sampled quarterly, one sampling per season, at each port. Depth strata were defined to cover the whole area where the trawling fleet operates regularly, i.e. continental shelf (20–200 m depth), upper slope (200–400 m depth) and lower slope (400–700 m depth). Each of the 420 hauls conducted was geolocated with a GPS device to calculate trawled distance that, together with the horizontal opening of the net mouth, was used to calculate the swept area to standardize density. Depth was estimated calculating an average point between the start and end points of each haul. Mesh size was stablished by law, i.e. 40-mm square-mesh everywhere but in Palamós lower slope, which was 50-mm squared-mesh for the blue and red shrimp fishery. After each haul, a representative fraction of the ML caught was collected and brought to the laboratory.

2.2.2. Marine litter characterization

The ML characterization follows the application of the Directive EU 2019/883 of the European Parliament and of the Council regarding monitoring data methodologies and the format for reporting passively fished waste (EU 2022/92). The ML fraction analyzed was only macro marine litter, items of marine debris that can be visually identified with the naked eye (GESAMP, 2019). In summary, six categories were defined as metal, plastic, rubber, textile, wood, and other waste, as described in Table 1. The analyses have not included clinker, which is the remnant of burned coal from steamships that sailed the Mediterranean in the eighteenth and nineteenth centuries. Approximately a century has passed since this type of litter was last produced, and it is not listed among the official categories of ML items in the mentioned Directive EU 2019/883. In the laboratory, all items were classified and weighted to the nearest $\pm$0.1 g.

Table 2
Mean ($\pm$ SE, standard error) density (kg km^2) for the six categories of marine litter obtained in the bottom trawl sampling surveys. Contribution of each category regarding the total amount of marine litter by weight is expressed in percentages. Minimum and maximum values for each litter category were calculated without considering the zero values.

Category	Mean density (kg km^{-2})	Contribution (%)	Range (min-max) (kg km^{-2})
Metal	2.09 $\pm$ 0.96	3.27	0.02–44.56
Plastic	5.35 $\pm$ 0.79	63.42	0.01–158.07
Rubber	1.97 $\pm$ 0.78	1.11	0.02–10.78
Textiles	1.01 $\pm$ 0.21	6.29	0.01–29.02
Wood	4.46 $\pm$ 0.55	19.27	0.02–32.92
Other waste	2.90 $\pm$ 0.70	6.63	0.02–34.17
Total	8.22 $\pm$ 1.00	100	0.01–201.94

In order to analyze the differences in ML density across categories, a Generalized Linear Model (GLM) was used. The selected family error distribution was "quasi-poisson" since the data set contained many zero values (i.e., ML categories that did not appear in a haul). The choice for the most appropriate link function and error distribution was made based on residual analyses. The goodness of the fitted model was tested with a Chi-Squared test based on residual deviance and degrees of freedom. The GLM analysis was done with R-4.3.0 package mgcv and pairwise comparison with the package emmeans (R, 2013). To assess the spatial distribution of ML density, all categories recorded in each haul were considered together.

2.3. Fishing effort effects on marine litter density

To evaluate the effect of fishing effort on the ML density in the area of the study, the total fishing time of the bottom trawl fleet (in hours) accumulated per km^2 was calculated quarterly for each haul. Fishing effort was obtained from Vessel Monitoring System (VMS) data. The VMS is a satellite-based monitoring system that provides data from fishing vessels (position, speed and course) to the fisheries authorities in order to control fishing activities, allowing the calculation, after data treatment, of the fishing time (h) in space (Sala-Coromina et al., 2021). A Generalized Additive Model (GAM) was used in order to analyze the effect of fishing effort on the spatial distribution of ML density (kg km^2). GAMs are flexible regression models that allow for non-linear relationships between the explanatory variables. The sampling location (latitude and longitude) was considered and the accumulated fishing effort in each sampling location was included as a spatially varying effect using a tensor product smooth in the model, as fishing effort varies across space.2.4. Spatial distribution of marine litter density.

2.3.1. Factors affecting marine litter

The influence of land-related variables in the ML distribution was studied using GAMs. The factors considered that may affect the distribution of ML include: (1) sampling location (latitude and longitude were considered as smoother in the base model), (2) season and (3) depth strata, which were incorporated in the model as categorical variables. Four distances were considered as land-based ML sources and were included as splines in the GAM model: (1) distance to the main city, (2) distance to river mouths, (3) distance to the coast, and (4) distance to a waste water treatment plant (WWTP) submarine outfall. These four land-based ML sources were identified as the most important ones in the study area. A total of 127 rivers, passing through the main industrialized areas and discharging water into the sea, and 147 submarine outfalls distributed along the coast were considered (Fig. 1). The city of Barcelona, whose population exceeds 1.5 million inhabitants, was considered the unique major city on the entire Catalan coast. Other coastal cities have at least 2 orders of magnitude less inhabitants. Distances to land-based ML sources (i.e., Barcelona, river mouths, WWTP submarine outfalls, and coast) were calculated as the minimum great circle distance between the sampling haul and the selected ML land-based source using *st_distance* from *sf* R package. Each sampling haul was assigned a single distance value for each stressor. Correlation between distances was tested in the model through *corplot* package (R, 2013).

2.3.2. Spatial marine litter density prediction

The spatial distribution of ML density from the continental shelf to the lower slope of the Catalan continental margin was predicted using

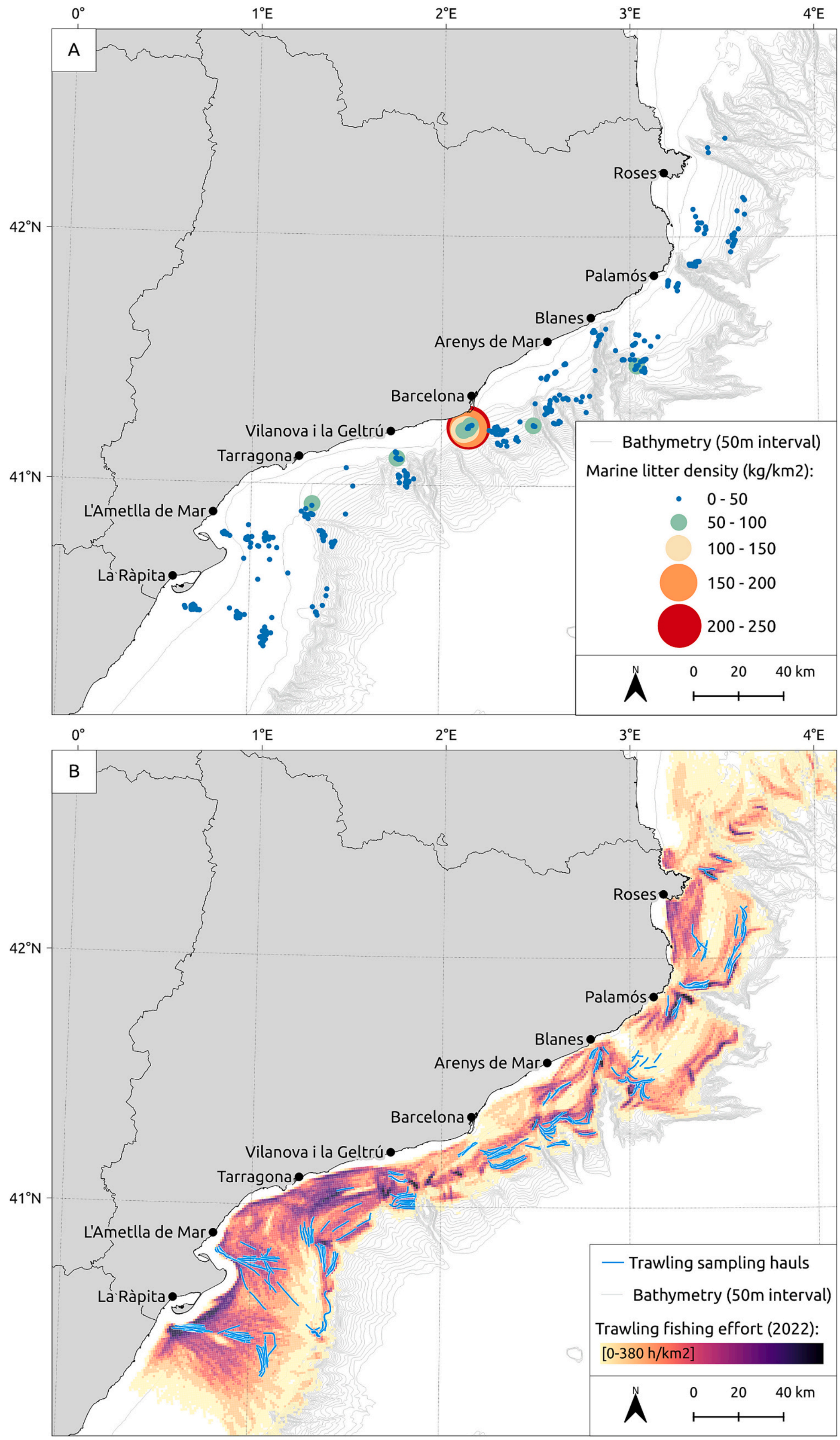

Fig. 2. A) Spatial distribution of density (kg km^{-2}) of seafloor marine litter recorded in the bottom trawl sampling surveys, represented each by colored circles. B) Spatial distribution of bottom trawling fishing effort (hours km^{-2}) in 2022. Blue lines represented each bottom trawl sampling haul. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Summary of the results from the Generalized Additive Model (GAM). The following contributing parameters explain the distribution of marine litter density from the continental shelf to the lower slope in the Catalan continental margin. For each of the parameters and terms analyzed, the significance interval is expressed as the following: (***) $p < 0.001$ and (**) $p < 0.01$ (*) $P < 0.05$ (.)$P < 0.1$. edf: effective degree of freedom; Ref.df: reference degree of freedom.

Model: ML density (kg km^{-2}) ~ s(Latitude, Longitude) + te(Latitude, Longitude, by = fishing effort)
Deviance explained: 42.9 %
$R^2 = 0.38$

Smooth terms	edf	Ref.df	F	*p*-value	
s(latitude, longitude)	21.359	25.398	7.024	$< 2*10^{-16}$	***
ti(Latitude, Longitude, by = fishing effort)	1.001	1.002	0.127	0.484	ns

the best fitted model considering land-related variables: season, depth and distances from the four land-based ML sources (main city, river mouth, coast and submarine outfall). The studied factors mentioned above were selected by a backward stepwise approach to determine the most parsimonious model. One term was removed from each model and each model was compared based on the lowest Akaike's Information Criterion (AIC) value. This was used to evaluate the goodness of fit and to determine the optimal number of model parameters, retaining only the significant explanatory variables. Data analysis was performed using the *mgcv* package in R software version R-4.3.0 (R, 2013).

3. Results

3.1. Marine litter characterization and spatial distribution

The ML density, in total and by category, is described in Table 2. Bottom trawl hauls with presence of ML accounted for 97 % of the total hauls, with a mean density of 8.22 ± 1.00 kg km^2. When studied by category, a great variability was observed as the densities of the different ML categories differed significantly (ANOVA; $F_{5,\ 2418} = 46.14$, $p < 0.001$) (Table 2; Supplementary Material Table S1). Plastic accounts for 63.42 % of the total weight of ML in the area, with an average density of 5.35 ± 0.79 kg km^2 and a hot spot showing a mean plastic density as high as 158.07 kg km^2. The category with the lowest density was textiles, with a mean value of 1.01 ± 0.21 kg km^2. The pairwise comparison between each ML categories is shown in Supplementary Material Table S2).

The spatial distribution of ML (all categories included) showed higher values off Barcelona, where densities of up to 201.94 kg km^{-2} were recorded. The lowest values were observed in the northern and southern limits of the study area (Fig. 2). The spatial distribution of plastic density showed a similar pattern to that observed when considering all ML categories combined (Supplementary Material Fig. S1). Plastic was the most prevalent type of debris found in trawling hauls. The correlation between total marine litter density —including all categories— and plastic density per haul is shown in Supplementary Material Fig. S2, with an R^2 value of 0.90.

3.2. Factors affecting marine litter

3.2.1. Fishing effort

The ML density varied spatially and the sampling location (latitude and longitude) had a significant effect on its distribution. However, no significant relation was found between the spatial distribution of ML density and the accumulated fishing effort in each sampling area (Table 3).

3.2.2. Spatiotemporal factors

The scientific surveys were performed seasonally at three different depth strata. According to season, the highest mean values of ML density were obtained during spring (9.34 ± 2.46 kg km^{-2}) and the lowest during autumn (6.44 ± 1.43 kg km^{-2}) (Fig. 3a). In terms of depth strata, the highest mean ML density values were found on the continental shelf (11.60 ± 1.91 kg km^{-2}), the shallowest depth stratum, while the lowest mean values were obtained on the lower slope (4.15 ± 0.97 kg km^{-2}) (Fig. 3b). However, although the mean ML densities between seasons and between depth strata were different, the medians did not differ much, as the dispersion of ML density between each categorical factor was high, indicating that there were some areas that acted as ML hot spots at certain times (Fig. 3a and b).

3.2.3. Potential land sources

According to land-based ML sources, four distances were considered to affect the distribution of ML density, including distances to a main city (i.e. Barcelona), river mouths, the coast, and submarine outfalls. These outfalls include those connected to wastewater treatment plants as well as those that function independently without any connection to such facilities. Regarding these potential sources, a decrease of ML density was observed as the distance from potential land sources increased. Marine litter hot spots (densities >100 kg km^{-2}) were always observed at distances <20 km from the land sources (Fig. 3c to 3f).

3.3. Spatial marine litter density predictions

According to the GAM, the best model explaining ML density in the Catalan continental margin includes: sampling area (latitude, longitude), distance to river mouth and distance to submarine outfall (Table 4). This model explained 46.8 % of the total deviance observed on the spatial distribution of ML density (Table 5). Based on the model results (Table 5), sampling location ($p < 0.001$, DE = 94.67 %) was the main factor explaining the spatial distribution of ML density. However, the best model also includes distance to river mouth ($p = 0.02$, DE = 2.74 %) and distance to submarine outfall ($p < 0.02$, DE = 2.59 %). Although these distances explained less variability of ML density, they were determinant to predict its spatial distribution. Fig. 4 illustrated the model predictions regarding the spatial distribution of ML density, indicating that the highest densities were located in the vicinity of Barcelona, near Tarragona and in the continental shelf between Palamós and Blanes. In agreement with the model predictions, there was a lower ML density in the north and south boundaries of the Catalan continental margin. The correlation between model predictions and observed ML density in each point is shown in Fig. 5 with a r-square of 0.56.

4. Discussion

This study provides valuable insights into the accumulation of ML on the seabed in the NW Mediterranean, focusing on fishing grounds along the Catalan continental margin. Marine litter was detected in 97 % of the hauls sampled at depths between 20 and 700 m, indicating that its widely distributed along the totally of the seafloor where the Catalan trawling fleet operates (20-700 m depth). Similar results were reported in other Mediterranean studies, with ML occurrence rates of 90 % (Spedicato et al., 2019), 88 % (Alomar et al., 2020) and 86 % (Garofalo et al., 2020) in sampling sites ranging from 10 to 800 m. Despite its widespread presence, the distribution of ML is highly variable, with density values ranging from 1.4 kg km^{-2} in the Balearic Islands (Alomar et al., 2020) to 1536.6 kg km^{-2} in the Catalan coast (Ramirez-Llodra et al., 2013). The densities of ML found in the present study (0.01–201.94 kg km^{-2}) are in accordance with those reported in western Mediterranean waters, exhibiting a highly heterogenous distribution pattern. Plastic was the most predominant category, accounting for 63.42 % of the total ML weight caught in the fishing nets. This is consistent with global trends (Bergmann et al., 2015) and with results from other Mediterranean regions. For example, Kouvara et al. (2024) reported plastic bags as the most common item at depths between 50 and 350 m in the Aegean Sea and Fortibuoni et al. (2019) reported

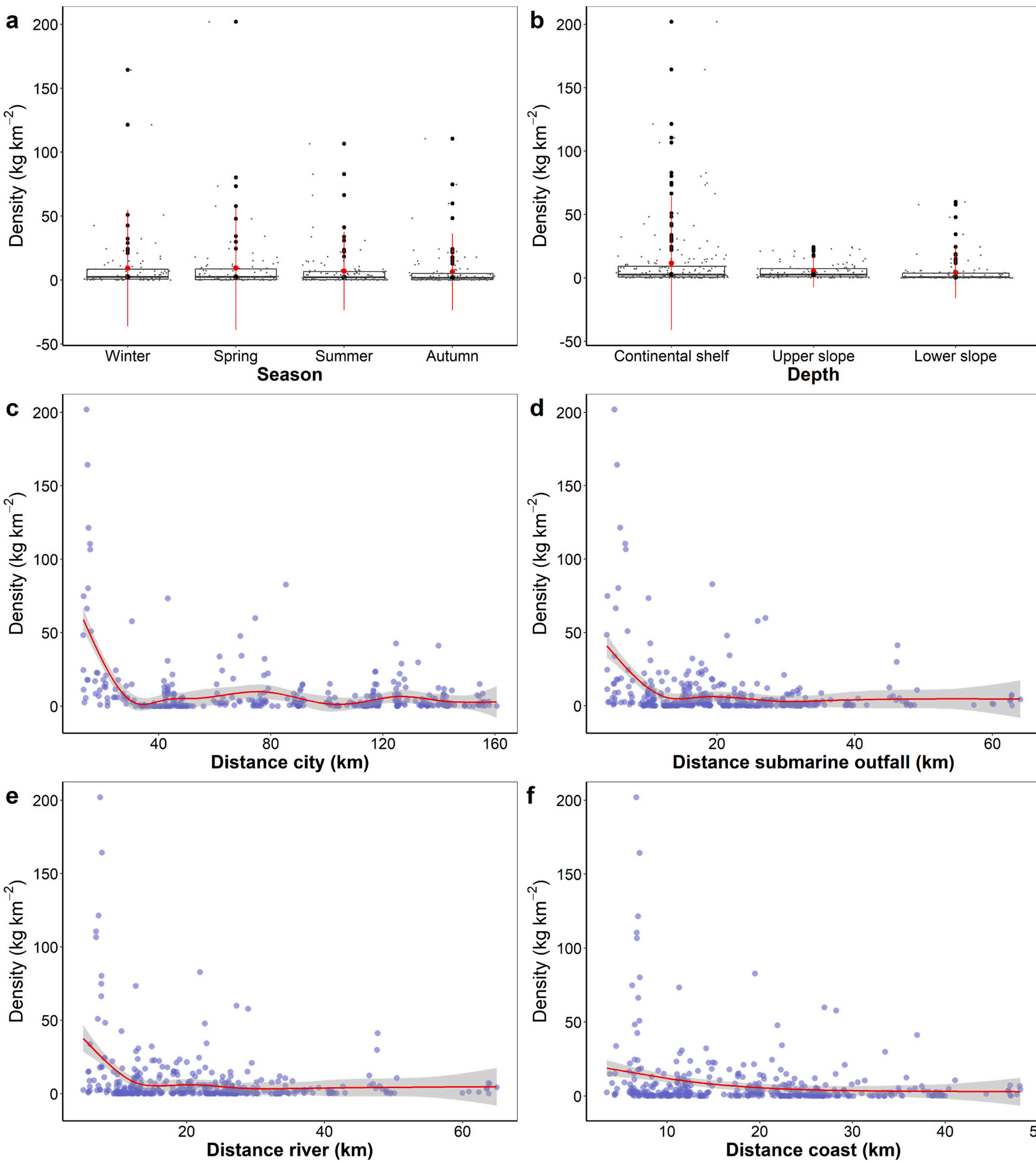

Fig. 3. Marine litter density for each of the factors used to model its distribution in the Catalan continental margin. Season and depth strata were represented with boxplots detailing the median (black lines), the mean (red dot), deviation from the mean (red vertical lines), outliers (values higher than 1.5 interquartile ranges) (black dots), first and third quartile (box lower and upper boundaries mark) and values for each haul (grey dots) (a and b). The correlation with distances were plotted with scatter plot showing the smooth correlation (red line) and each confidence interval (in grey) (c, d, e and f). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

industrial plastic packaging as the dominant category in the Ionian and Adriatic Sea. Mistri et al. (2024) reported highlight fishing gear as the most prevalent item in fishing grounds of the Adriatic Sea but the material used to make this gear was again plastic. Previous studies in the same area (Balcells et al., 2023), found also plastic to be the most common type of marine debris due to its widespread use, low weight and slow degradation rate. The widespread findings of plastic being the type of ML mostly caught in trawling nets may vary in quantity in different Mediterranean studies. For example, lower weight contributions, i.e. 38 % (Alvito et al., 2018) or 25 % (Alomar et al., 2020) were observed in

Table 4

Summary of the model selection approach for the Generalized Additive Models (GAMs) based on the R-squared (R^2) and Akaike's Information Criterion (AIC). All models included the spatially explicit terms for longitude and latitude as the base model and a backward stepwise approach was applied where the contribution of each covariate was considered from the initial full model. Relevant models for the GAM approach are described here being the fifth model (in bold) selected as the best for describing the spatial and temporal distribution of marine litter density.

Model	R^2	AIC
ML density (kg km^{-2}) ~ s(Latitude, Longitude) + season + depth strata + s(distance city) + s(distance river mouth) + s (distance cost) + s(distance submarine outfall)	0.425	3348.78
ML density (kg km^{-2}) ~ s(Latitude, Longitude) + depth strata + s(distance city) + s(distance river mouth) + s(distance cost) + s(distance submarine outfall)	0.428	3344.18
ML density (kg km^{-2}) ~ s(Latitude, Longitude) + s(distance city) + s(distance river mouth) + s(distance cost) + s (distance submarine outfall)	0.432	3340.29
ML density (kg km^{-2}) ~ s(Latitude, Longitude) + s(distance city) + s(distance river mouth) + s(distance submarine outfall)	0.432	3339.33
ML density (kg km^{-2}) ~ s(Latitude, Longitude) + s (distance river mouth) + s(distance submarine outfall)	**0.434**	**3338.49**
ML density (kg km^{-2}) ~ s(Latitude, Longitude) + season + depth strata	0.420	3351.13

Table 5

Summary of the results from the best-fit Generalized Additive Model (GAMs) after the backward stepwise model selection. The following contributing parameters explain the distribution of marine litter density from the continental shelf to the lower slope in the Catalan continental margin. For each of the parameters and terms analyzed, the significance interval is expressed as the following: (***) $p < 0.001$, (**) $p < 0.01$, (*) $p < 0.05$, and (.) $p < 0.1$. edf: effective degree of freedom; Ref.df: reference degree of freedom. DE: deviance explained.

Model: ML density (kg km^{-2}) ~ s(latitude, longitude) + s(distance river mouth) + s (distance submarine outfall)

Deviance Explained 46.8 %

Smooth terms	edf	Ref.df	F	p-value		Partial DE (%)
s(latitude, longitude)	21.305	24.955	8.662	< 0.001	***	94.67
s(distance river mouth)	2.047	2.393	3.874	0.02	*	2.74
s(distance submarine outfall)	1.003	1.004	5.791	0.02	*	2.59

the Western Mediterranean Sea. The mean plastic density of our study (5.35 ± 0.75 kg km^{-2}) was higher than the value reported in the surrounding grounds of the Balearic Islands (2.73 ± 0.26 kg km^{-2}; Alomar et al., 2020), but much lower than the densities observed during a MEDITS survey along the Spanish Mediterranean seafloor (8.4 ± 50.0 kg km^{-2}; García-Rivera et al., 2018) and in Sardinian waters (7.35 ± 2.37 kg km^{-2}; Alvito et al., 2018), and significantly lower than in the Central Adriatic Sea (49 ± 25 kg km^{-2}; Pasquini et al., 2016). Apart from plastic, other materials including metal, rubber, textile, wood and other waste were also caught, but their contribution was significantly lower compared to plastic, as documented in previous studies (Alvito et al., 2018; Balcells et al., 2023).

Seasonal variations in ML distribution have yielded contrasting results across different studies. In the present study, no significant differences were observed in the spatial distribution of ML among seasons. The data showed high variability, suggesting that certain areas act as ML hotspots at specific times of the year. Similar findings were reported by Alomar et al. (2020), who found no significant seasonal differences in ML accumulation along the coast of the Balearic Islands, suggesting that local environmental and anthropogenic factors may influence seasonal trends differently across regions. In contrast, Campana et al. (2018), observed higher ML densities during spring and summer, likely driven by the increased tourism and marine activities. The spatial distribution of ML density exhibited significant variability both vertically and horizontally, with certain areas acting as a litter accumulation hotspot. A similarly patchy distribution was documented by García-Rivera et al. (2017), where higher ML densities were found at shallower depths, exceeding 10 kg km^{-2} in some areas of the Spanish Mediterranean continental shelf. Similarly, in Sardinian waters higher concentrations of ML were observed above the continental margin compared to deeper areas, with a maximum of 26.6 kg km^{-2} (Alvito et al., 2018). Even greater accumulations have been reported in other studies, as in Erüz et al. (2022), where coastal ML densities surpassed 1200 kg km^{-2} in the southern Black Sea shelf. In contrast, other studies documented that the highest densities of ML were found in submarine canyons, driven by hydrodynamic processes that transport litter down to deep waters (Tubau et al., 2015). Consistent with these observations, Pham et al. (2014) observed spatial variability in ML density and composition across European sites, with submarine canyons exhibiting the highest abundances. Although high-energy water flow events can facilitate transport of ML to deep waters, certain materials, such as wet wipes and denser plastics —originating from land-based sources —tend to accumulate closer to shore, particularly at depths shallower than 400 m (Soto-Navarro et al., 2020). In agreement with these findings, our study identified the highest ML densities on the continental shelf (depths <200 m), reinforcing the role of land-based sources and proximity to urban areas in shaping ML distribution patterns on the seafloor. While land-based inputs may be an important source of ML, natural factors such as wind and currents should also be considered in explaining the higher densities of ML in shallower depths (Bergmann et al., 2015; Galimany et al., 2019). Moreover, different debris material possesses varying physical properties and shapes, which can influence their transport and deposition behavior. Incorporating data on the physical characteristics of each debris type —such as density, buoyancy, and degradation rates— could improve the understanding of the processes governing ML spatial distribution.

Marine litter is primarily linked to land-based sources, which contribute approximately 80 % of the total waste found in the ocean (UNEP, 2009). As a result, shallow marine areas near densely populated urban regions are likely to accumulate higher levels of anthropogenic litter (Galimany et al., 2019; Koutsodendris et al., 2008). In this study conducted along the Catalan continental margin, the highest ML density (201.94 kg km^{-2}) was found in the surroundings of Barcelona, one of the most populated areas in the western Mediterranean with significant industrial activity. The type of litter found in densely populated areas may differ from other areas; for example, a previous study reported that most of the ML found in the Barcelona area was wet wipes (Balcells et al., 2023). This type of waste is associated to the effects that crowded urban areas have on the marine environment as they relate to different anthropic uses including household baby and personal care (Hadley et al., 2023). The spatial model predicted higher ML accumulations just below Barcelona, Palamós and Tarragona. These critical accumulation zones, located downstream of these three cities, can be explained by the predominant north-to-south current along the Catalan continental margin (Font et al., 1988; Martínez et al., 2024) and the location of river mouths southward of the urban centers. In contrast, lower litter densities were observed at the northern and southern edges of the study area, with lower population densities and probably less affected by industrialization and urbanization of the coast. Beyond urban discharge, especially from densely populated areas, other land-based sources such as river mouths and submarine outfalls are demonstrated to play a key role in the distribution of ML density in coastal areas. Similar results were reported by Enrichetti et al. (2020), who observed higher densities of ML, predominantly plastics, in proximity to river mouths along the Ligurian

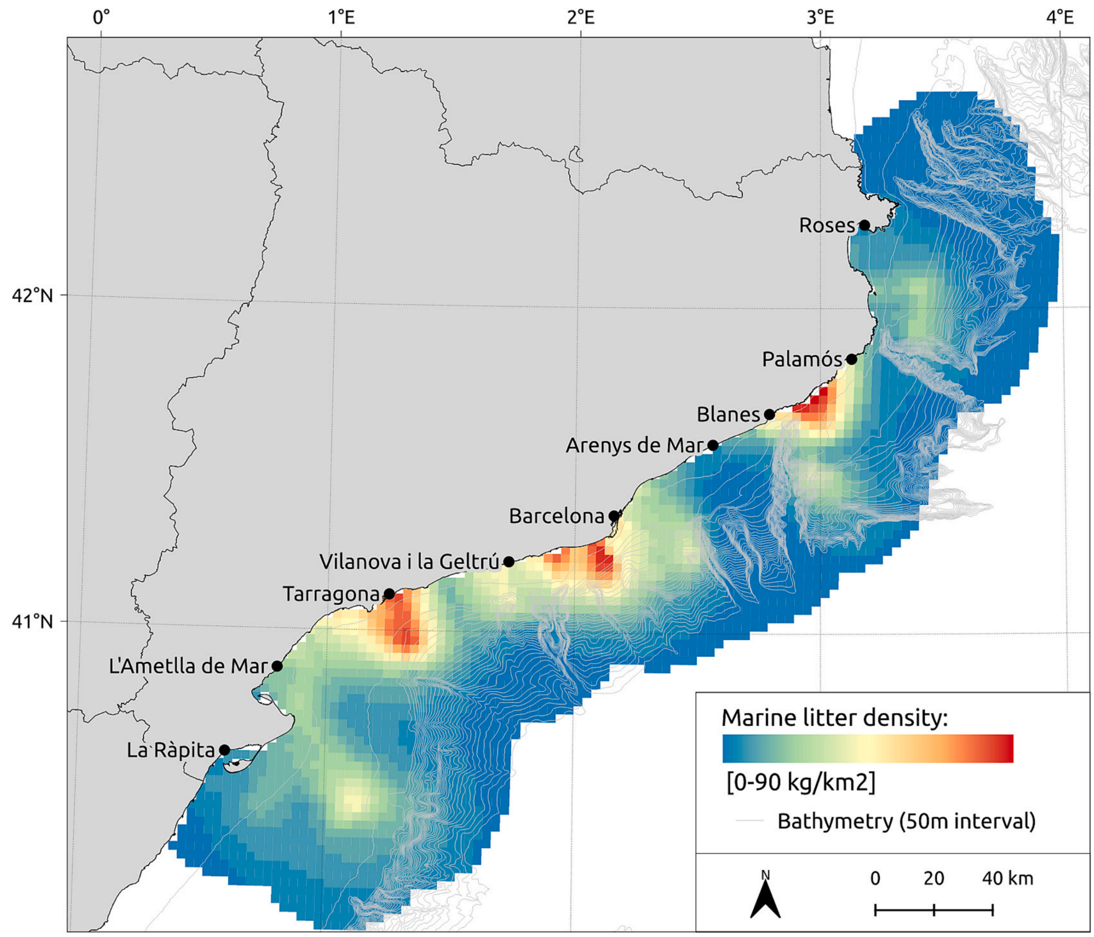

Fig. 4. Output map from Generalized Additive Model (GAM) predicting the spatial distribution of marine litter density in the Catalan continental margin.

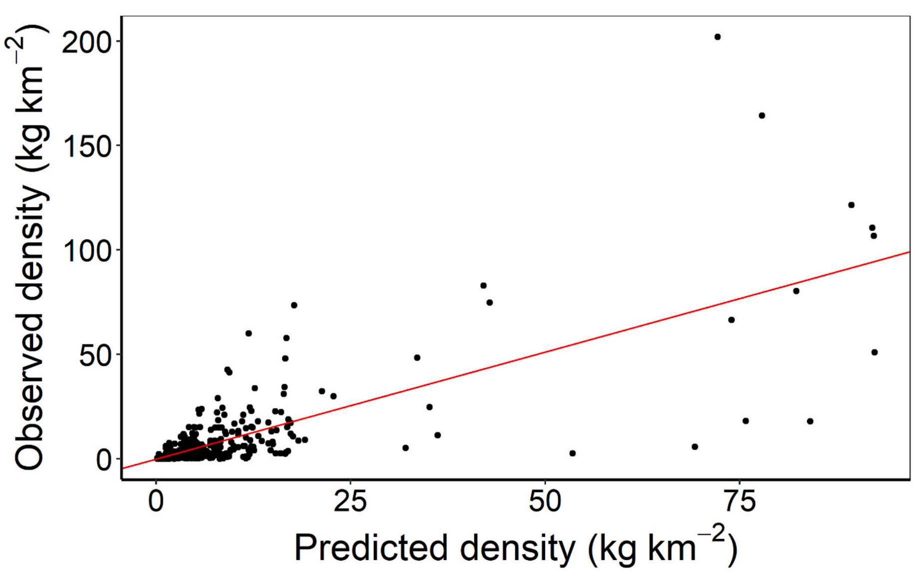

Fig. 5. Correlation between observed and predicted marine litter density (kg km^{-2}) in the Catalan continental margin.

continental shelf. Likewise, Schirinzi et al. (2020) estimated that approximately 0.4–0.6 t of plastic annually enter the Mediterranean Sea via two major rivers in the surroundings of Barcelona, providing further evidence that riverine discharge serves as a significant pathway for debris transport into marine ecosystems. Despite the existence of waste water treatment plants (WWTPs), deficiencies in collecting and treating urban waste water have been documented, leading to the continuous discharge of waste into marine environments through submarine outfalls (Rodríguez-Villanueva and Sauri, 2021). Additionally, extreme weather events, which are projected to be more common under climate change scenarios, poses a further challenge. Further analysis of the spatial distribution of ML would be valuable to explore potential links between ML accumulation and rainfall events, as well as the resulting river discharges. However, the quarterly sampling frequency used in this study does not allow for a direct correlation between such short-term events and the observed ML accumulations. The increment of surface runoff and sewage overflows during such events, is expected to exacerbate the transport of untreated waste into coastal and marine ecosystems, contributing to the accumulation of marine debris in the seafloor (Lincoln et al., 2022). This underscores the urgent need for enhanced wastewater management strategies and resilient infrastructure to mitigate the environmental impacts associated with urban discharge, while simultaneously highlighting the importance of reducing litter input from terrestrial sources to prevent ML accumulation.

Several strategies have been implemented in order to address the ML issue, including the EU Plastic Strategy (COM/2018/028 final), the Mediterranean and Regional Action Plans against ML, and Fishing for Litter (FFL) initiatives (KIMO, 2015). Our results indicate that fishing effort did not significantly influence the spatial distribution of Marine litter in Catalan fishing grounds, suggesting that litter removal by the bottom trawl fleet alone is insufficient to reduce the persistence of high-density ML areas. The role of fishers and FFL strategies, though, is crucial to promote education engaging all stakeholders to tackle this issue (Mannaart and Bentley, 2022). In Catalonia, the initiative from the Catalan fisheries Federation Pescaneta (https://pescaneta.com/) aims to accomplish this goal promoting sustainable practices through advertisement and an itinerant exhibition freely available to the public. But there is the need to complement seabed clean-up efforts, such as FFL initiatives, with measures targeting the reduction of terrestrial ML inputs at their sources (Ronchi et al., 2019). To address this challenge effectively, strategies should prioritize minimizing mismanaged waste in metropolitan areas and implementing mitigation measures to prevent plastic litter from entering aquatic environments, such as rivers, before reaching the ocean (Schirinzi et al., 2020; Wang et al., 2024). Additionally, it is crucial to thoroughly examine the processes through which land-based litter flows into marine environments (Wang et al., 2024). Furthermore, all proposed strategies must strengthen national capacities to develop robust policies on pollution control and ML prevention. A key management measure is the implementation of the single-use plastic directive at the national level in Spain (Fortibuoni et al., 2025). In the study area, this should specifically focus on addressing the use and disposal of wet wipes. Broader recommendations to reduce ML in the studied area, and globally, include the promotion of sustainable societies increasing recycling rates, reutilization of materials, awareness within society, and tourism and industry waste policies. Addressing ML is not solely an environmental issue but also one with significant economic, health, safety, and cultural implications.

5. Conclusions

The study underscores the importance of improving land-based waste management to prevent further accumulation of ML in the ocean, particularly in highly urbanized coastal areas. Reducing inputs from rivers and wastewater outfalls, especially near densely populated urban areas such as Barcelona, is crucial to mitigate the problem. This research highlights the critical need for coordinated efforts between land-based waste management, policy-making, and marine conservation to reduce the input of ML into the Mediterranean Sea.

CRediT authorship contribution statement

Marta Blanco: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Marc Balcells:** Writing – review & editing, Data curation. **Víctor Martín-Vélez:** Writing – review & editing, Methodology, Data curation. **Joan Sala-Coromina:** Writing – review & editing, Methodology, Formal analysis. **Jordi Ribera-Altimir:** Writing – review & editing, Software. **Ferran Bustos:** Writing – review & editing, Data curation. **Joan B. Company:** Writing – review & editing, Funding acquisition, Conceptualization. **Eve Galimany:** Writing – original draft, Supervision, Conceptualization.

Declaration of competing interest

Marta Blanco: I have nothing to declare.
Marc Balcells: I have nothing to declare.
Víctor Martín-Vélez: I have nothing to declare.
Joan Sala-Coromina: I have nothing to declare.
Jordi Ribera: I have nothing to declare.
Ferran Bustos: I have nothing to declare.
Joan B. Company: I have nothing to declare.
Eve Galimany: I have nothing to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2025.118167.

Data availability

Data will be made available on request.

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