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Artisanal trawl fisheries as a sentinel of marine litter pollution

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ABSTRACT

Systematic seafloor surveys are a highly desirable method of marine litter monitoring, but the high costs involved in seafloor sampling are not a trivial handicap. In the present work, we explore the opportunity provided by the artisanal trawling fisheries to obtain systematic data on marine litter in the Gulf of Cadiz between 2019 and 2021. We find that plastic was the most frequent material, with a prevalence of single-use and fishing-related items. Litter densities decreased with increasing distance to shore with a seasonal migration of the main litter hotspots. During pre-lockdown and post-lockdown stages derived from COVID-19, marine litter density decreased by 65 %, likely related to the decline in tourism and outdoor recreational activities. A continuous collaboration of 33 % of the local fleet would imply a removal of hundreds of thousands of items each year. The artisanal trawl fishing sector can play a unique role of monitoring marine litter on the seabed.

1. Introduction

Marine litter has become one of the global environmental problematics in the XXI century (Bernal et al., 2016). Plastic pollution turns to be not only an environmental, but also economic and human health problem (Desforges et al., 2015; Rochman et al., 2015; Wilcox et al., 2015), triggering a global onrush of mitigation initiatives. The popularity of single-use plastic, used for a limited time before being discarded, contrasts with its high durability and persistence in the environment, which makes this material the main component of global litter (Morales-Caselles et al., 2021). As a result, tackling plastic pollution is part of the United Nations Sustainable Development Goals (SDG, Target 14.1) (UN SDG14, 2016), and the Group of Seven (G7) countries agreed to an Action Plan to Combat Marine Litter (G7 Summit, Japan 2016) (G7, 2015), which was expanded to G20 countries shortly afterwards (G20 Summit, Germany 2017) (G20, 2017). In the European Union, the Marine Strategy Framework Directive (MSFD) (2008/56/EC) requires Member States to take action to achieve or maintain good environmental status (GES) of their marine waters and includes the *Descriptor 10 concerning marine litter* (Galgani et al., 2013). The EU Plastics Strategy focuses on the transition toward a more circular economy with special attention on single-use plastic items. During the Fifth session of the United Nations Environment Assembly (UNEP, 2022) governments agreed to adopt a global Plastic Treaty by the end of 2024.

Despite the high-profile nature of these actions against marine litter, it is difficult to evaluate their effectiveness because there is no harmonized and comparable monitoring in place. Plastic is everywhere, and some accidental or deliberate release into aquatic ecosystems seems unavoidable (Ross and Morales-Caselles, 2015). Marine litter is highly diverse, comprising items of various sizes, shapes and materials and there are different factors such as the composition or environmental variables that will determine the fate of these items in the marine environment (Barboza et al., 2018). There is growing evidence that litter will eventually accumulate on the seafloor (Canals et al., 2021; Nakajima et al., 2021; Navarrete-Fernández et al., 2022), and that the near-shore seabed can act as the main sink for macro-litter (Morales-Caselles et al., 2021; Olivelli et al., 2020; Onink et al., 2021). However, monitoring and particularly the recovery of seafloor litter reservoir can be complex and costly due to accessibility itself (Roman et al., 2020).

Research on seafloor macro-litter has increased rapidly in recent years, but it still falls behind the number of studies conducted in other environments (Canals et al., 2021). Most of the deeper seabed data has been collected through opportunistic surveys by means of trawl fishing (Maes et al., 2018). Fisheries have been attributed to be one of the main

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sources of marine litter pollution (Lavers and Bond, 2017; Lebreton et al., 2022; Ruiz et al., 2022), and simultaneously it is an economic sector heavily affected by marine litter in a variety of ways, all of which result in either reduced revenues or increased costs (Chabaud, 2019; Nguyen and Brouwer, 2022). Fishermen can play a significant role in the monitoring, prevention and removal of marine litter (Nguyen and Brouwer, 2022; Ronchi et al., 2019). Trawl fisheries have already provided important seabed litter information in the Mediterranean (Fortibuoni et al., 2019; García-Rivera et al., 2017; Olguner et al., 2018; Saladié and Bustamante, 2021), Atlantic Ocean (Kammann et al., 2018; Maes et al., 2018), Gulf of Mexico (Wei et al., 2012) and the Pacific Ocean (Keller et al., 2010; Nakajima et al., 2021).

The origin of marine litter is linked to a variety of human activities from production, fishing, transportation and consumption, where plastic items from take-out food and beverages predominate (Morales-Caselles et al., 2021). The COVID-19 pandemic brought unprecedented levels of disruption to these activities, resulting in significant social and economic impacts throughout the world. In many countries, including Spain, the population lockdown during the 2020 COVID crisis led to the interruption of social life, commerce or the transport of people and goods. In this sense, and beyond the tragic known impacts to human lives and livelihoods, a focussed analysis on the consequences of COVID-19 limitations in terms of marine litter density and composition provides an exceptional natural experiment to monitor the relationship between human activity and the production of marine litter.

The present study aims to characterise and monitor the marine litter in the nearshore area of the Gulf of Cadiz (SW Spain) from 2019 to 2021 while testing the hypothesis of a possible reduction in the input of marine litter as a consequence of the COVID-19 lockdown.

2. Materials and methods

During the years 2019, 2020 and 2021 a total of 18 artisanal trawl fishing boats from the Fishermen's Association of Sanlúcar de Barrameda and Puerto de Santa María (Cádiz, SW Spain) collaborated with the ECOFISH project to collect an overall of 181 trawls along the seabed near the mouth of the Guadalquivir River in the Gulf of Cadiz (Table 1). In this particular study, only artisanal fisheries, as defined by the Food and Agriculture Organization, participated in the sampling. This includes traditional fisheries involving fishing households, using relatively small fishing vessels (varies among countries) and a small amount of capital and energy, making short fishing trips, close to shore, mainly for local consumption (FAO, 2022).

2.1. Data collection

The methodology to obtain and classify the samples was designed based on the experience of the ECOPUERTOS project (ECOPUERTOS, 2013) (Fig. S1). Every journey, each cooperating trawler performed between 2 and 4 hauls using a fishing net with a 4 cm mesh size. For each trawl, the route of the boat was recorded with a GPS tracker and the time intervals of the hauls noted. Hauls were carried between 10 and 70 km from the coast at depths ranging from 10 to 580 m. Once on board, the content of the net was sorted, separating the litter items into a labelled sack. Upon return to port, the content of each marked sack was placed on a predesigned canvas (Fig. S2), with its correspondent label. Each item was classified using a joint master litter category list (JML) (Morales-Caselles et al., 2021) and a picture was taken for the records. The data was then transferred to a spreadsheet for processing.

2.2. Data treatment

Litter densities were calculated considering the number of items collected per area trawled in each haul, for both mathematical and spatial analysis. Density maps were prepared using Geographic Information System software (QGIS®) based on the WGS84 coordinate reference system (EPSG 4326). First, a shapefile was generated in the form of a mesh with pixels the size of a 32-fraction of a degree in an area (M1). Next, the georeferenced tracking or hauls in shapefile format (H1) including the area and the number of items retrieved was added. A new shapefile of pixels (M2) was then generated, where each pixel of M2 is the result of the sum of the values of the variables of each of the hauls of H1 intersecting each pixel of M1 (Fig. 1). So, all the items by category and their sampled area were added from all the transects of H1 that are within a specific pixel of M1. Thus, the whole set of items collected throughout an entire haul were considered for the computation of concentrations per area, as per the uncertainty of the exact point at which the items were collected throughout the haul (they might have been collected at the beginning, at the end, in an intermediate zone or the sum of the entire transect). Therefore, we assumed that the probability of finding that number of items is the same throughout the entire haul.

The area-weighted mean density (González-Fernández et al., 2022) of each category in M2 was determined through the quotient of the sum of the number of items in the category and the sum of the area sampled in each pixel,

$$[\mathscr{X}]_p = \left(\frac{\sum_n x}{\sum_n A} \right)_p$$

where $[\mathscr{X}]_p$ is weighted average density for pixel *p*, *x* is the number of items collected in the haul and *A* is the area covered by the net in the haul. The area-weighted mean takes into account the relative importance of each haul in terms of the area sampled. It reduces the overestimation effect of small hauls with a high number of articles (high concentrations in this haul) compared to using an arithmetic mean. Therefore, the variability of the hauls, regarding the location and the area sampled, reveals differences in the area sampled in each pixel. For this reason, a minimum area (0.6 km^2 per pixel) is set to consider litter concentration results as valid. However, pixels with a smaller area were not removed, as they provide additional information on the concentrations in the environment. These pixels were designated with a hatching.

Results were analysed by season for all years sampled according to the natural cyclical time periods into which the year is divided. The winter season contains the months of January to March, summer

Table 1
Summary of basic information related to the litter samplings both each season and different pandemic stages during the ECOFISH Project.

Attributes	Total hauls sampled	Summer	Autumn	Winter	Pre-Lockdown	Lockdown	Post-Lockdown
Number of tows	181	99	61	21	94	44	43
Number of items	2463	1389	844	230	1596	594	273
Number of plastic items	1809	950	670	189	1230	433	146
Date (Beginning)	6/17/19	June	September	January	6/17/19	8/6/20	6/16/21
Date (Finish)	9/15/21	August	December	March	1/17/20	3/12/21	9/15/21
Low depth (m)	10	13	13	10	14	10	13
Near distance (km)	10.79	10.89	10.79	11.32	10.79	11.31	12.36
Far distance (km)	68.22	68,22	41.69	36.14	61.61	37.46	68.22
Total sampled area (km^2)	88.61	49.47	28.94	10.20	43.97	21.28	23.36

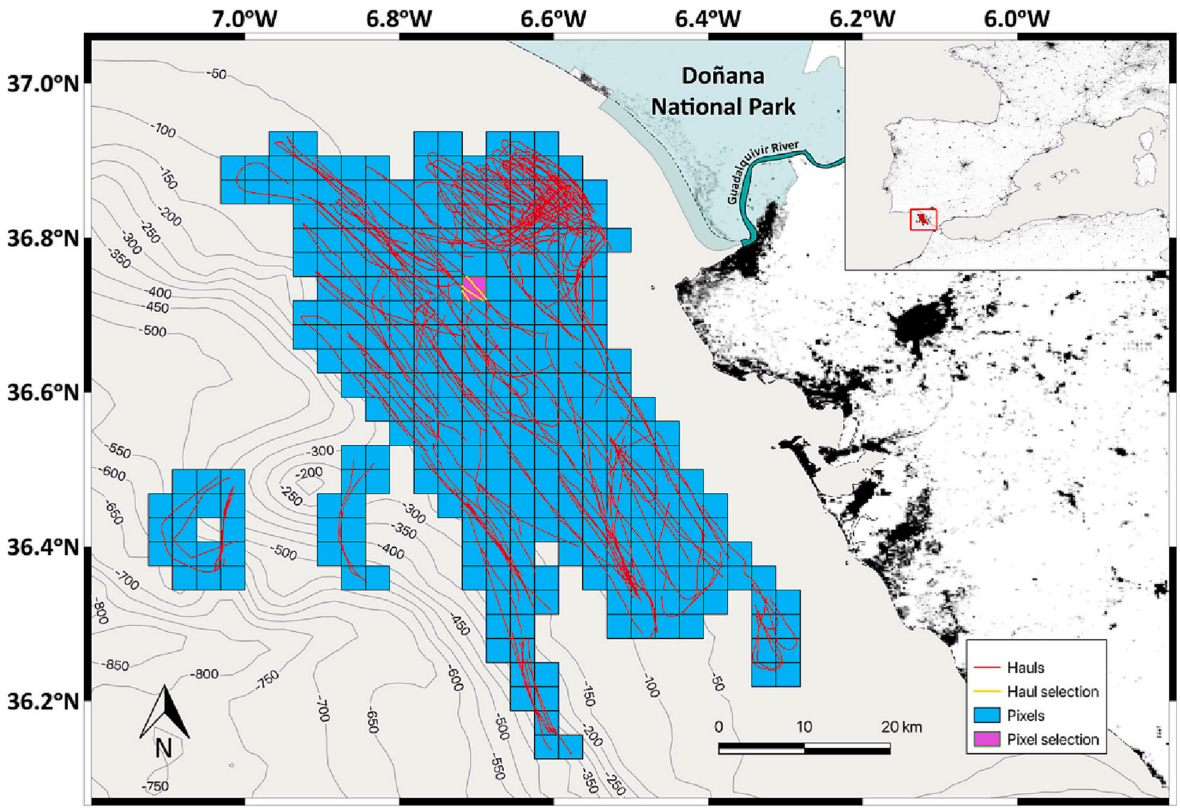

Fig. 1. Representation the hauls (red) performed by fishermen and the 1/32 degree grid (blue). Each selected pixel (violet) holds a selection of hauls used for the litter density calculations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

includes the months of June to August and autumn covers the months of September to December. No data were recorded for the months of April and May, so it was not possible to establish the spring period.

Additionally, a preliminary annual analysis was performed that led to a more focused exploration taking into account the context of the COVID-19 disease. The time pandemic periods were divided according to the validity of the Decree Laws passed by the Spanish government (Table 1). These decrees limited the mobility and activities of the Spanish civil society, where only strictly essential activities (health, food and security sectors) were allowed to operate in-person from March 2020 and for a whole year. This period of time was called "State of Emergency" in Spain. Hence, these periods have been divided into pre-lockdown, lockdown and post-lockdown. A spatial analysis shows the variability of litter density during these pandemic periods. In order to reflect the intensity of increase or decrease of litter density per pixel along the years, linear regressions among the three main periods were determined and the slopes were calculated for comparison.

Finally, average recovery rates (*RR*), per boat and day (*ij*), of litter removed (*z*) were calculated for all samples (*n*) from each of these periods (*s*). These rates serve as indicators of the variability of the concentration and accumulation of litter on the seabed over the years.

$$\left(RR_{ij}\right)_s = \left(\frac{\sum z_{ij}}{\sum n_{ij}}\right)_s$$

The amount of litter removed by the fishing fleet in the Gulf of Cadiz over a period of time is determined by the product of the rate $(RR_{ij})_s$ and the number of boats and days.

2.3. Statistical analysis

In addition to common descriptive statistics and the area-weighted mean density, statistical analyses were carried out in order to give consistency to the results obtained for each case. Data sets did not show a normal distribution (Shapiro Wilk test, $p < 0.05$) and their variance was not homogeneous (Levene's test, $p < 0.05$). Therefore, statistical differences in marine litter density between seasons and pandemic periods were analysed using non-parametric statical test Kruskal-Wallis, for all the trawls performed. Furthermore, Spearman's rank tests (ρ) were used to explain the relationship between the marine litter densities by generic categories and the distance to coast, which is applicable to non-normally distributed data.

3. Results

Eighteen artisanal fishing trawling boats participated in the collection of seabed litter in the Gulf of Cadiz between the years 2019 and 2021. A total of 2463 litter items larger than 2 cm were retrieved from 181 hauls covering a total area of 88,607 km^2 in the Gulf of Cadiz. Overall, 98 % of the hauls collected litter (there were three trawls without any trash). The sampling effort varied, with the maximum hauls performed during summer, with a total of 99 hauls collecting an overall number of 1389 items in an area of 49,476km^2. During autumn, 61 hauls were performed in 28,937 km^2 with a total of 844 items retrieved. In the winter months, 21 hauls collected a set of 230 items sampled in 10,194 km^2. The number of hauls, items and the sampled area at each stage of the pandemic period can be found in Table 1.

3.1. Litter composition

Overall, litter was composed by plastic (73 %) followed by metal (14 %), textile (6 %), glass and ceramics (4 %), processed wood (1 %) and rubber (1 %). This trend was kept during the 3 sampling years. The top-3 items were composed by single-use items including cans (11 %), wrappers (11 %) and plastic bags (9 %), followed by fishing lines and cords (8 %), 10–20 cm film fragments (6 %) and food containers (6 %) (Fig. 2, Table S1). The composition and structure of certain types of items

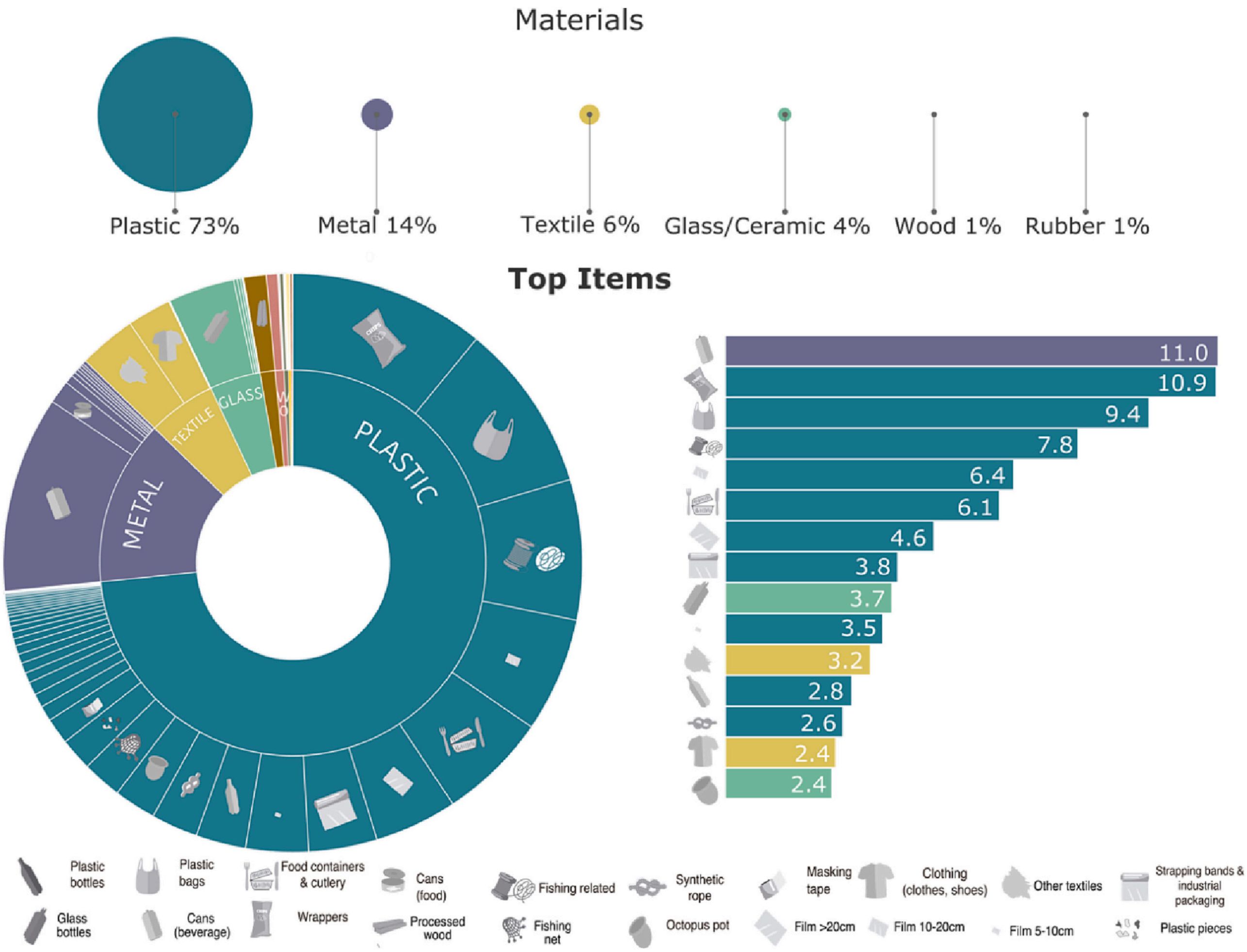

Fig. 2. Overall composition and top items (%) retrieved in the ECOFISH project.

facilitates their grouping into generic categories for better comparability between areas and analysis of distribution patterns. In this way, the categories of main film-type items (films fragments, wrappers and bags), fishing-related items (synthetic ropes, fishing nets and fishing lines, string and cords) and beverage and food cans (beverage cans and food cans) were described. The results obtained allowed us to compare the Gulf of Cadiz with other geographical areas of the world (Fig. S3, Table 2).

Seasonality showed that main film-type items reached the first position in the ranking of top-items collected not only in the summer, but also during the autumn and winter hauls (30 %, 41 % and 45 %, respectively). On the other hand, when considering pandemic stages, main film-type items were the most abundant waste during pre-lockdown and lockdown (36.5 % and 37.2 % respectively), whereas during post-lockdown months, beverage and food cans were relatively more prevalent (26.3 %).

3.2. Litter density and distribution

Sampling in the Gulf of Cadiz shows a wide range of concentrations (0–396 items/km^2), with an area-weighted mean of 24 ± 17 items/km^2. For a spatial distribution analysis, a total of 293 pixels represents the area-weighted mean density of total litter in the sampled area (Fig. 3). This map shows an apparent and heterogeneous decrease in the density of total items as the distance to the coastline increases, with densities between 68 and 2 items/km^2 per pixel. Specifically, the central section, located in the south of the river mouth, showed the highest concentrations, followed by the southern and the northern sections, respectively.

The analysis of the distribution of the generic categories (Fig. 4, Table S2), combined with an analysis of correlations (ρ), allows us to observe the trends in the accumulation of these litter. The density of fishing-related items shows a homogeneous distribution in the area analysed ($\rho = 0.075$, $p = 0.389$). Beverage and food cans increase in density with distance from the coast ($\rho = 0.209$, $p = 0.006$), whereas film-type items are more abundant close to land with lower concentration at more distant locations ($\rho = -0.206$, $p = 0.004$).

Temporal variability in litter concentration was limited among seasons, showing no significant differences (Kruskal-Wallis test, H = 2.45, df = 2, $p > 0.05$). The area-weighed mean reached 25 ± 17 items/km^2 in summer, followed by 25 ± 18 items/km^2 in autumn, and 16 ± 11 items/km^2 in winter. However, the spatial distribution of maximum litter concentrations during seasons presented differences along the sampled areas. These differences were found between the South-East and West during the summer season, and the North-East during the autumn and winter time (Fig. S4).

Our results from the preliminary annual analysis showed stable litter densities during the first years of the study with a decreasing trend of concentrations in 2021. This observation, together with the lack of a meaningful seasonal variability in litter densities, led to a more in-depth exploration of the data considering the pandemic context caused by COVID-19 in this particular region. Regarding the COVID period, there were significant differences in litter concentration across the pandemic stages (Kruskal-Wallis test, H = 61.36, df = 2, $p < 0.05$). In general, there was a decreasing trend in the area-weighted mean from the pre-lockdown months 32 ± 17 items/km^2 followed by the lockdown 23 ± 15 items/km^2, to the post-lockdown 10 ± 7 items/km^2 (Fig. 5).

Table 2
Summary of seabed litter density (items/km^2) and percentage (%) by material and category in different regions of the world.

Regions	Location	Mean density (items/km^2)	Plastic (%)	Metal (%)	Glass (%)	Other Material (%)	Main film-type items (%)	Fishing-related items (%)	Beverage and food cans (%)	Other Categories (%)	References
Northeastern Atlantic	Gulf of Cadiz (Spain)	$2.4 \cdot 10^1$	73.45	13.84	4.26	8.44	35.24	12.63	12.26	39.87	This study
	Northeastern Atlantic Ocean	$4.5 \cdot 10^1$	71.16	3.78	2.45	22.60	8.27	36.95	1.76	53.03	(ICES, 2018; OSPAR, 2018)
Mediterranean	Gulf of Alicante (Spain)	$1.8 \cdot 10^1$	56.99	32.14	0.00	10.87	0.00	18.92	26.59	54.49	(García-Rivera et al., 2017)
	Northwestern Mediterranean Sea	$2.3 \cdot 10^2$	89.18	2.49	2.98	5.35	55.91	13.75	1.56	28.78	(Gerigny et al., 2019)
	Alboran Sea (Spain)	$2.9 \cdot 10^2$	77.12	14.83	3.12	4.93	21.16	1.61	13.77	63.45	(Morales-Caselles et al., 2021)
	Eastern Mediterranean Sea	$5.7 \cdot 10^2$	82.89	7.49	4.44	5.18	34.95	11.87	7.22	45.95	(Ioakeimidis et al., 2014)
	Mediterranean Sea	$4.2 \cdot 10^3$	86.13	1.08	3.60	9.19	43.06	7.03	0.00	49.91	(Sánchez et al., 2013)
Black Sea	Constanta Bay (Romania)	$2.9 \cdot 10^2$	45.25	21.88	22.38	10.49	12.89	9.49	9.99	67.63	(Ioakeimidis et al., 2014)
Sea of Japan	Tokyo Bay (Japan)	$2.7 \cdot 10^2$	56.05	39.02	2.26	2.67	24.09	2.16	34.03	39.73	(Kuriyama et al., 2003)
Northeastern Pacific	Western Coast of the US	$6.2 \cdot 10^1$	27.96	34.74	12.65	24.65	10.96	2.67	25.64	60.73	(Keller et al., 2010)
Western Atlantic and Caribbean	Gulf of Mexico	$3.5 \cdot 10^2$	15.57	3.28	53.54	27.61	2.07	10.23	1.54	86.16	(Wei et al., 2012)
	Southeastern Caribbean Sea	$2.5 \cdot 10^3$	30.20	19.31	39.11	11.39	10.40	16.34	7.92	65.35	(Debrot et al., 2014)

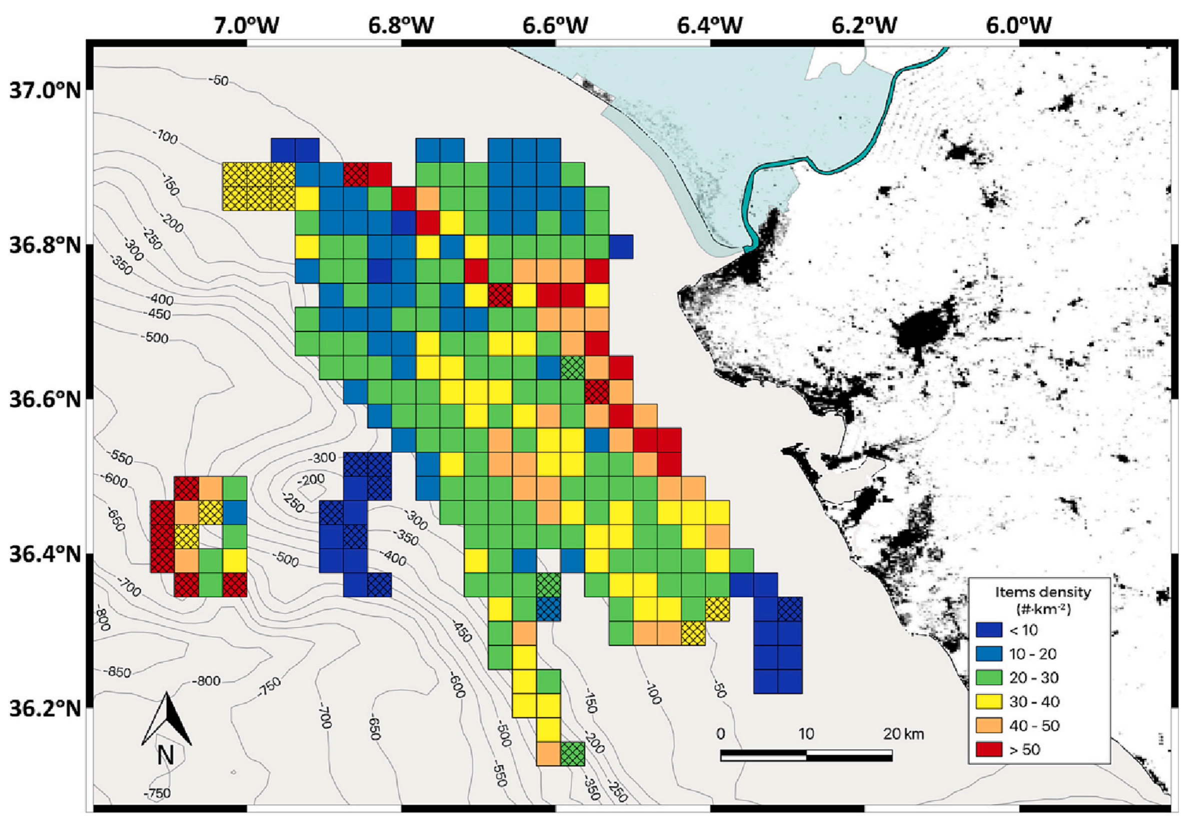

Fig. 3. Average density distribution of litter (#items/km^2) in the Gulf of Cadiz. Each pixel represents 1/32 degree. Pixels with relatively small sampling area (< 0.6 km^2) are indicated by a lined pattern.

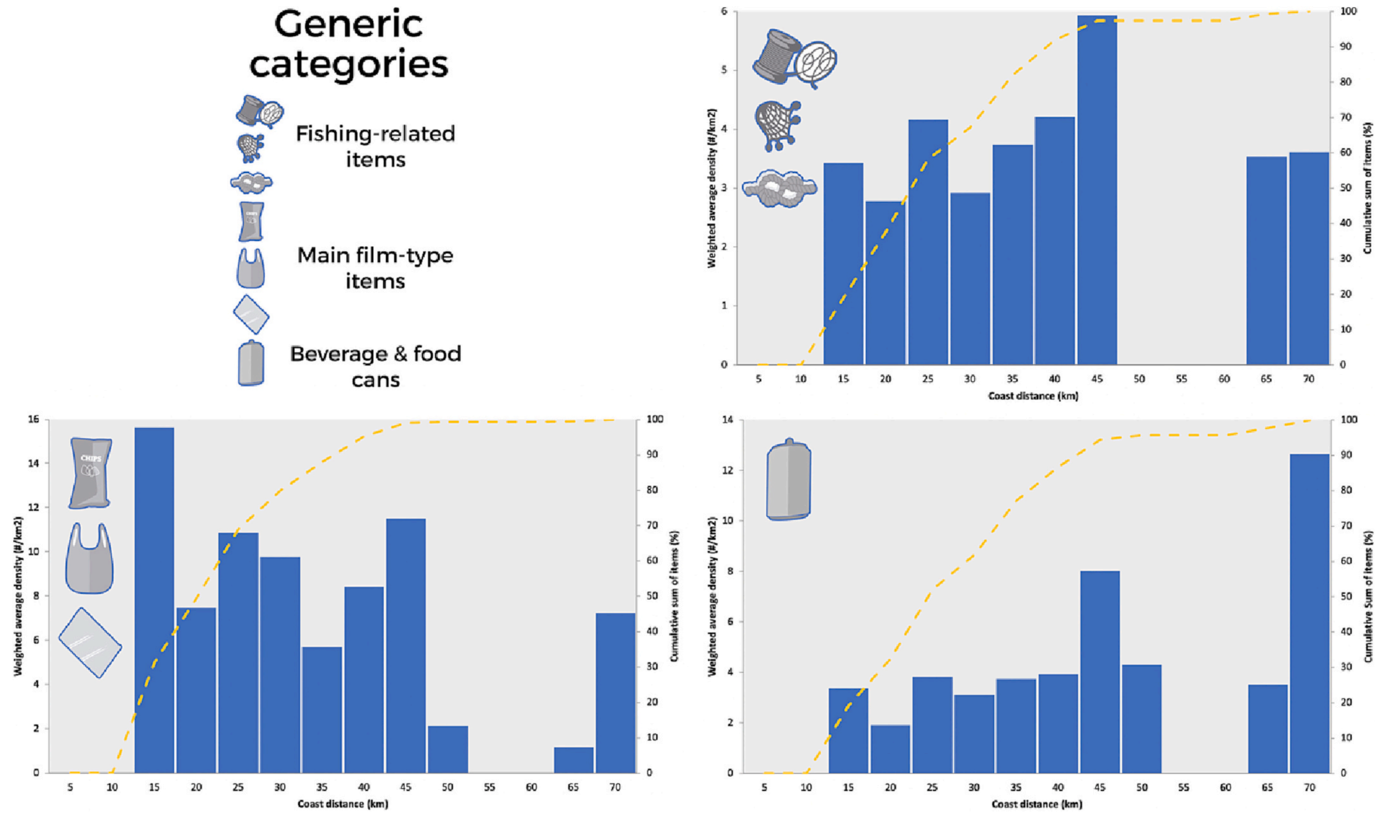

Fig. 4. Area-weighted mean density (#/km^2) of (a) fishing-related items including fishing lines, nets and ropes (top-right), (b) main film-type items including bags, wrappers and film fragments (bottom-left) and (c) beverage and food cans (bottom-right) versus distance to coast (km).

In addition, litter concentrations decreased at different rates throughout the stages of the pandemic, depending on their general category and potential origin. The concentration of film-type items decreased between pre-lockdown and post-lockdown from 12 to 2 items/km^2. Fishing-related items from 4 to 1 items/km^2, while cans show a minor decrease with a stable concentration around 3 items/km^2. For a spatial distribution analysis, the area-weighted mean of litter concentration in the sampled areas indicate a sequential decrease in the pandemic stages (Fig. 6). The highest concentration was found in the pre-lockdown and the lowest during the post-lockdown. However, litter concentration between these stages was found to vary heterogeneously across the area analysed (Fig. 7).

Finally, in order to estimate the potential of trawlers to remove litter from the seabed, two scenarios were considered for the analysis of litter recovery rates varying the collaboration of the fishing fleet. The first considering only the artisanal fishing trawling boats that collaborated in the sampling (RRa), and the second if the entire fishing fleet of the collaborating guilds had removed the rubbish (RRb) (De la Cruz et al., 2022). In both cases, a decrease in litter recovery rates is observed in the succession of each stage of the pandemic (Table 3).

4. Discussion

4.1. Seafloor litter composition in the Gulf of Cadiz and other world areas

The study is located in front of the mouth of the Guadalquivir River, an important contributor to the biological productivity and fisheries of the Gulf of Cadiz (Bermúdez et al., 2021; Campo and Prieto, 2009; de Carvalho-Souza et al., 2019), as well as a potential source of land-based litter (González-Fernández et al., 2021).

Our results reinforce the findings of previous studies in terms of relative abundance of materials (Debrot et al., 2014; García-Rivera et al., 2017; Gerigny et al., 2019; ICES, 2018; Ioakeimidis et al., 2014; Keller et al., 2010; Kuriyama et al., 2003; Morales-Caselles et al., 2021; OSPAR, 2018; Sánchez et al., 2013; Wei et al., 2012), with plastic being prevalent (> than 50 % of the total litter), followed by metals and glass. However, there are differences among ecosystems such as bays, islands, ports or open ocean as well as among geographical regions (Mediterranean area, northern Europe, North America, the Caribbean and Asia).

Litter composition in the Gulf of Cadiz were comparable to those in other European areas, both the Mediterranean and Atlantic, with a prevalence of plastic-type waste (over 70 %). Exceptions appear in two locations, the Gulf of Alicante and the Bay of Constanta in the Black Sea, where concentrations of metal and glass material, respectively, were considerably higher. On the other hand, the European area varies with other parts of the world. The North American locations showed the greatest heterogeneity in material composition of the marine debris collected. However, in Tokyo Bay, the abundance of plastic materials increases followed by metal. These dissimilarities support the fact that the predominance of the types of marine debris is mainly influenced by the local and regional activities (Fig. S3, Table 2).

The quantification of the type and abundance of seabed items allows partially to elucidate the potential sources of litter, thus providing useful information to support preventive management actions. In the Gulf of Cadiz, after grouping the items into generic categories, the sum of the abundance of the 3 main types of marine debris (TOP-3) comprises the majority of the items collected (60 %) and is composed of main film-type plastic items (35 %), fishing-related (13 %), and metal single-use food items (12 %). The classification of the litter items showed a high heterogeneity in the sources (take-out consumption, household, industrial or fishing), echoing the variety of pressures in the Gulf of Cadiz.

The TOP 3 comparison for different regions revealed that they share between 1 and 2 categories of items with the TOP 3 of the Gulf of Cadiz. However, the sum of the abundances of the categories that make up this TOP 3 varies in each of the areas. In this sense, the main activity carried out in each comparison site can be observed (Fig. S3, Table 2). The

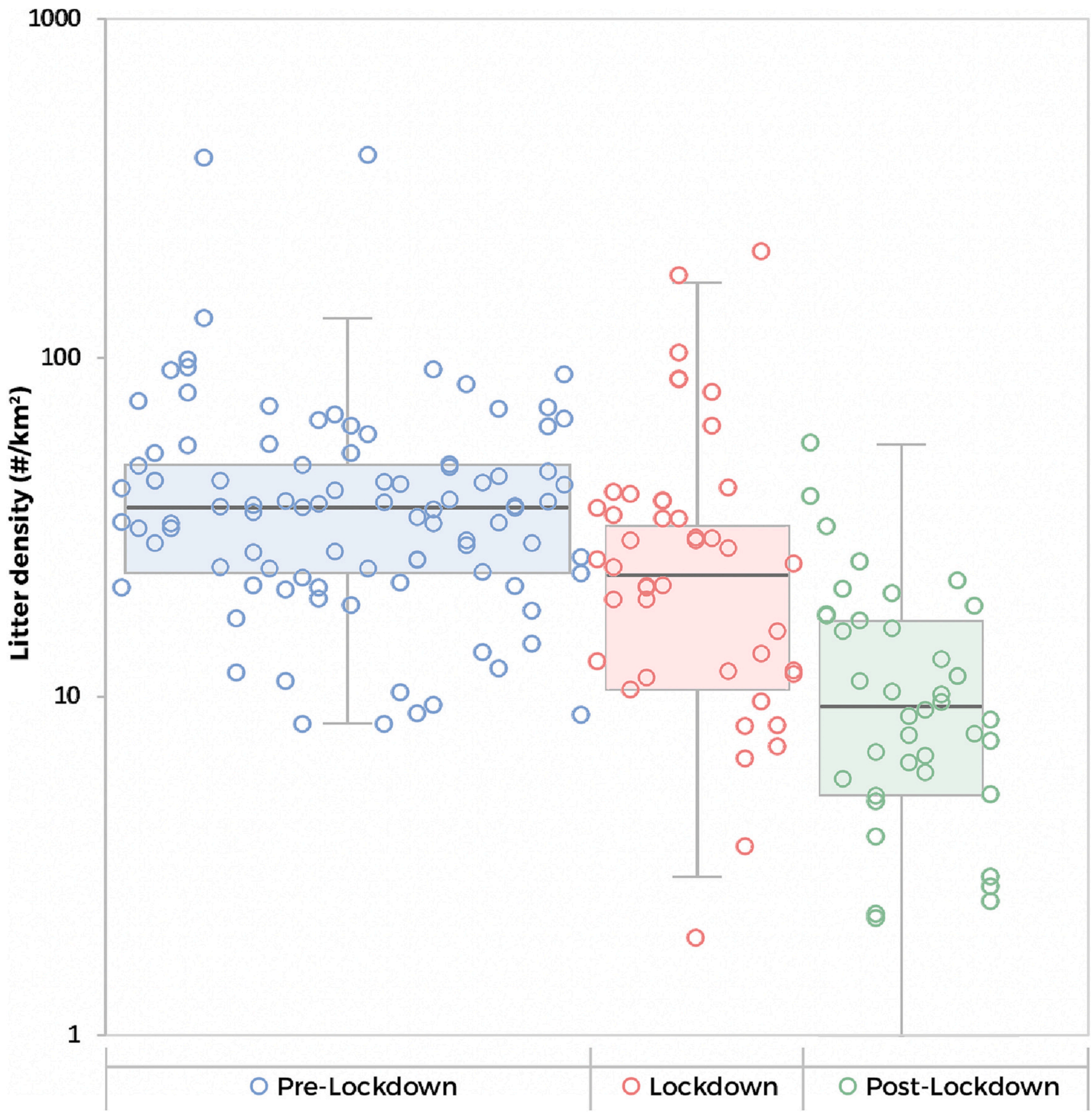

Fig. 5. Total density distribution of all hauls arranged by date, from 17th June 2019 to 15th September 2021. Colours account for the three different periods related to the COVID-19 pandemic: Pre-Lockdown (from 17th June 2019 to 17th January 2020, blue), Lockdown (from 6th August 2020 to 12rd March 2021, red), Post-Lockdown (form 16th June 2021 to 15th September 2021, green). Box-whisker plots describe data distribution for each period. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

American area, on average, differs the most in the sum of abundance of the TOP 3 in the Gulf of Cadiz (29 %), followed by the Black Sea (32 %). In both areas there is an important presence of single-use items, which leads to consider recreational activity as the main one. The European Mediterranean and Atlantic areas are more similar (51 %), with a slight difference in the Atlantic area where fishing activity has a greater impact. However, in both Tokyo Bay and north-western Mediterranean Sea, the presence of this TOP 3 is similar to the found in Cadiz (over 60 %), with recreational use likely to be the main source of impact in the area. This validates the cross-cutting nature of the environmental problem with these types of waste, initially caused by low social awareness, coupled with waste management deficiencies. Still, waste from fishing-related activities seems to be produced mainly due to accidental losses, and a low rate of immediate recovery, by crafts.

Regarding the litter density found in each location sampled by trawling techniques, the Gulf of Cadiz is one of the areas with the lowest concentration of litter. The north-eastern Atlantic area differs by 1 to 2 orders of magnitude from other parts of the world, including nearby areas in the Mediterranean Sea such as the Alboran Sea and Gulf of Lion in the north-western Mediterranean Sea. Different factors that account for relative lower densities in the Gulf of Cadiz may be related to the physical causes, such as oceanic dynamics or the orography of the seabed. Nonetheless, the anthropogenic influence is a key factor to be taken into account, as shown by the type of waste found in each area. This indicates that both physical and social factors determine the concentration of waste that ends up accumulating on the seabed.

4.2. Spatial variability on the distribution of the seafloor litter

The transport of litter in the ocean depends essentially on the intrinsic characteristics of each type of object (e.g. shape, size, buoyancy force) and the acting environmental forcing (e.g. water currents, waves), theoretically resulting in differential deposition along the seafloor (Haarr et al., 2022). Therefore, litter composition and concentration could vary according to the distance from shore.

On a global scale, the density of seafloor litter decreases as the

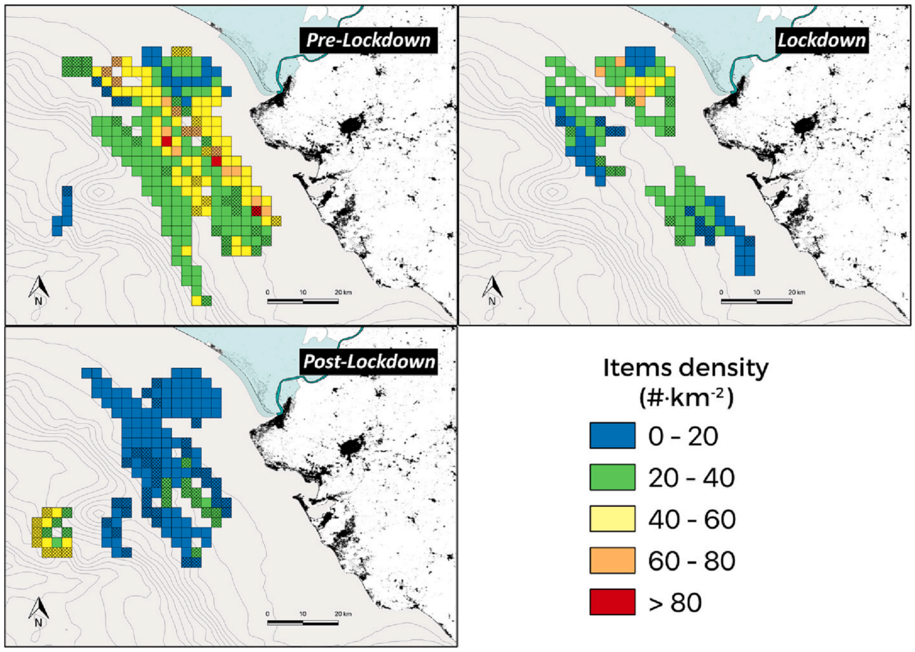

Fig. 6. Average density distribution of litter (#items/km^2) in the Gulf of Cadiz in pre-lockdown, lockdown and post-lockdown stages. Each pixel represents 1/32 degree. Pixels with relatively small sampling area (< 0.6 km^2) are indicated by a lined pattern.

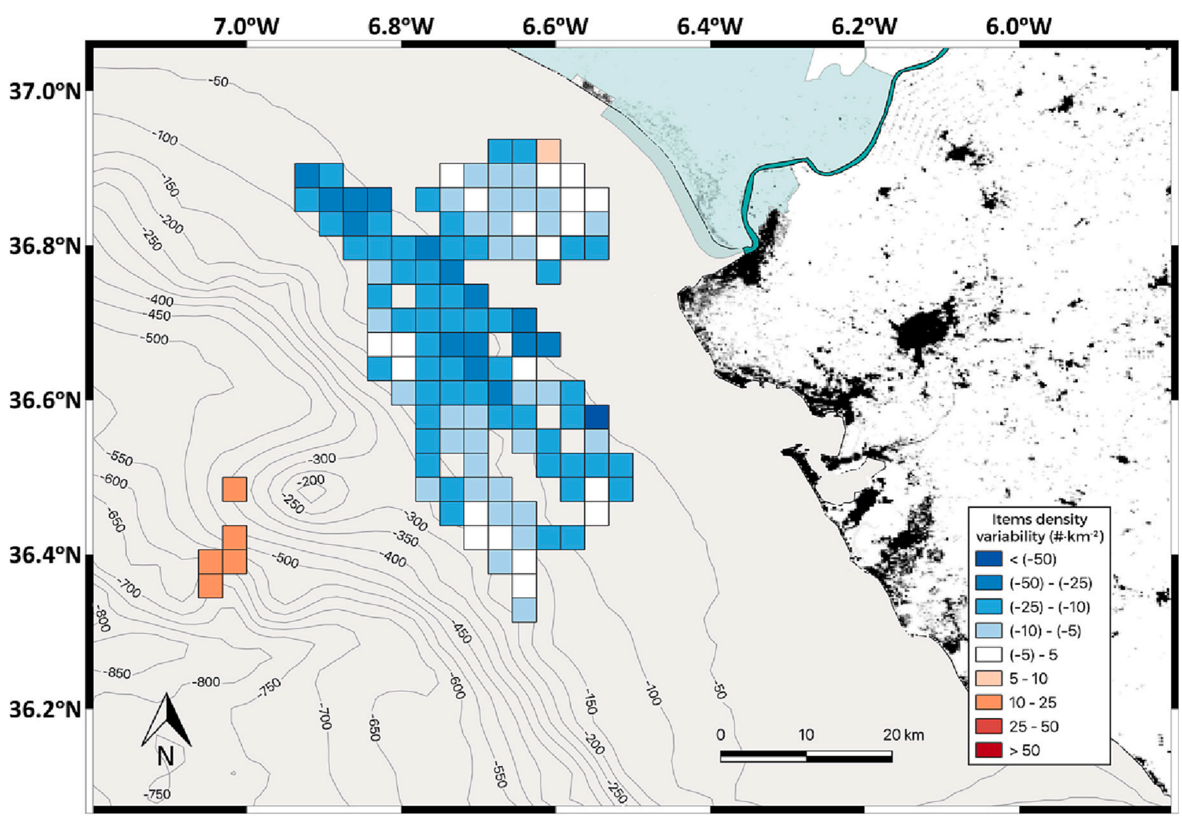

Fig. 7. Change in litter density (#items/km^2) from pre-lockdown to post-lockdown periods in the Gulf of Cadiz. Blue colours indicate decreasing trends while red colours show increasing trends. Each pixel is 1/32 degree. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

distance from the coastline increases (Morales-Caselles et al., 2021). At a local scale, however, other factors such as the nearby land-based litter sources, marine traffic, hydrodynamics, the seabed slope, or the seabed morphology (Pham et al., 2014) could generate divergences from the general decline pattern with distance to shore. In this case, a spatial analysis in the Gulf of Cadiz showed an apparently decreasing pattern up to 50 km from coast, and an additional maximum at 70 km from the coast (Fig. 3). A possible explanation could be related to the fact that an

Table 3

Average recovery rates (RR) of litter removed from each of pandemic stage. RRa considers the ships that collaborated during the project. RRb considers the entire fishing fleet. An average of 220 working days was used to calculate the annual recovery rates. Closed fishing days, public holidays and weekends were not included.

Scenarios	Number of artisanal trawl fishing boats	Recovery rates	Pre-Lockdown	Lockdown	Post-Lockdown
RR	1	Items·boat^{-1}·day^{-1}	55 ± 17	42 ± 20	20 ± 12
RRa	18	Items·partner boats^{-1}·year^{-1}	$2.2 \cdot 10^5 \pm 6.9 \cdot 10^4$	$1.9 \cdot 10^5 \pm 7.7 \cdot 10^4$	$7.7 \cdot 10^4 \pm 4.9 \cdot 10^4$
RRb	54	Items·fishing fleet^{-1}·year^{-1}	$6.5 \cdot 10^5 \pm 2.1 \cdot 10^5$	$5.0 \cdot 10^5 \pm 2.3 \cdot 10^5$	$2.3 \cdot 10^5 \pm 1.5 \cdot 10^5$

important share of the litter found offshore were relatively heavier objects, which will not tend to be transported long distances away (e.g., metal and weighty fishing objects) (Owiredu et al., 2022). Therefore, it can be inferred that these items likely came from fishing activities or maritime transport. Nonetheless, it should be noted that the number of experimental hauls in the area of litter concentration farthest from the coast was relatively low, so these data should be interpreted with caution.

In addition, the analysis of the types of marine debris would be useful to determine its possible origin and traceability in space. For the rest of the items, distributions patterns could be related to the discharge of water flow from the Guadalquivir River over a relatively wide and flat coastal shelf. In this sense, the analysis of the litter distribution by generic categories may help to better understand this process (Fig. 4, Table S2). In our study, lighter film-type items showed a decreasing density as the distance from the coast increased. Film-type plastics have a low buoyancy force, tending to sink more frequently than thick-walled plastic items (van Emmerik and Schwarz, 2020). Exposure to weathering can also more easily lead to fragmentation of these kinds of macroplastics, preventing them from being transported long distances (Ryan, 2015). Meanwhile, fishing-related items were evenly distributed throughout the study area and showed no relationship with the distance to shore. These particular items could be lost or dumped by professional and recreational fishing vessels present throughout the Gulf of Cadiz, allowing their occurrence at any distance from the coast (Buhl-Mortensen and Buhl-Mortensen, 2017). It is noteworthy that we found the concentration of beverage and food cans increased with distance from the coast. Cans typically show little mobility once they reach the sea (Pasquini et al., 2016; Strafella et al., 2015); they tend to fill with water or sediment and sink to the bottom of the sea, so they are not expected to travel long distances. This fact reinforces the idea that most of the cans found in this study could have been thrown directly into the sea from boats (Ioakeimidis et al., 2014; Koutsodendris et al., 2008).

Regarding seasonal variability, the province of Cádiz (SW Spain) is a popular national and international tourist destination, with a peak of outdoor and recreational activities in the summer period. On the other hand, the water discharge of the Guadalquivir River significantly intensifies in the winter months. These seasonal factors might influence the litter distribution on the seafloor. However, litter pulses from land may not be detected through the analysis of average densities for each station (Tramoy et al., 2022; van Emmerik et al., 2022). Therefore, for the seasonal analysis, the maximum area-weighted mean density was determined with the maximum for the month of each station. (Fig. S4).

Seafloor litter hotspots relocated throughout the year, and the seasonality of the discharges of the Guadalquivir Estuary, the tourism activity and the ocean currents are probably behind the change of location (Gomiz-Pascual et al., 2021; Hanebuth et al., 2021; Hernández-Molina et al., 2003). A spatial seasonal analysis showed that in summer the highest litter concentrations were found near the coast, at the south of the Guadalquivir River mouth, with a steady decrease in relation to the distance from land. Beaches are a landmark for summer recreational activities in the southern area. Therefore, litter concentrations in this area decreased significantly in autumn and winter, while the highest concentrations occurred to the north and in front of the mouth of the Guadalquivir River, closer to the Doñana National Park, an area off-limits to mass tourism. Autumn and winter rains likely wash away the litter retained on Guadalquivir riverbanks during the dry summer season.

4.3. Temporal trends

The recent global health emergency caused by the COVID-19 pandemic raised the possibility of studying the effect of the population lockdown on marine litter pollution. Previous studies have shown different patterns of change depending on the nature of the objects, with sanitary products, such as face mask, increasing by >80 times (Roberts et al., 2022).

In our study region, the mobility limitations on civil society established by the Spanish government during the State of Emergency caused a change in the habits of the population and their activities, which could have resulted in an effect on the litter inputs to the marine environment during and after the pandemic. During the pre-lockdown stage the monthly litter concentrations were stable, in addition, seasonal analysis along the whole time of the study did not show significant variations. However, the analysis of litter concentration revealed a progressive reduction from lockdown to post-lockdown, by 30 % and 70 %, respectively (Fig. 5). Furthermore, spatial analysis showed that the decrease in litter concentration covered the entire area of the Gulf of Cadiz (Fig. 6). However, litter concentration did not vary homogeneously in the analysed area of the Gulf of Cadiz (Fig. 7) between pre-lockdown and post-lockdown stages.

This generalized decrease in the litter concentrations could mainly derive from mobility constraints to the population, as they led to a major decrease in tourist activity. In the Andalusian region this translated into a loss of visitors of around 60 % during 2020 (BMIE, 2021). In addition, we should expect a delay between the decrease in littering from land-based sources and the possible decline in the amount of litter on the seafloor, due to the lag time from the time the litter is dumped on land, transported through drainage basins and rivers, and deposited on the seabed. Therefore, we suspect the impact of the decrease of recreational and tourist activities in 2020 was not mirrored on the seafloor litter in our area until the year 2021.

Other factors, such as the run-off from the Guadalquivir River, could also affect to a greater or lesser extent on the pattern of litter density in the area analysed. That being said, the peak flows of run-off observed were at similar levels during these years (Gomiz-Pascual et al., 2021). The temporal analysis of the data series provided by the hydrographic confederation of the Guadalquivir River (SAIH, 2022) indicates that the average run-off flows were $25 m^3/s$ during the years in which the sampling for our study was carried out with the trawlers (from 2019 to 2021). This indicates that there was an important and constant flow of water, with a continuous contribution of litter from both the riverbed and the banks of the Guadalquivir River. As such, we find no evidence that the decrease in marine seabed litter was due to a lack of run-off from the Guadalquivir.

Moreover, a marked decrease in the density of film-type plastic items (−79 %) was found, that might suggest a drop in the generation of outdoor recreational waste during the lockdown. Similarly, a decrease also occurred with fishing articles (−75 %), which could be linked to a decrease in sport and recreational fishing activities, either from land or from small crafts. In contrast, food and beverage cans did not have such a strong decrease (−20 %), which supports the view that a large fraction of the cans found in our sample come from the sea-based sources, as professional fishing and maritime transport continued as essential activities during the State of Emergency.

Finally, an analysis of litter recovery rates could verify, together with the previous analyses, the hypothesis that the reduction in litter concentration is an effect of the State of Emergency. Thus, a decrease in annual litter recovery rates by artisanal fishing trawling boats could be due to the foreseeable drop in waste arriving and accumulating on the seabed from river banks, the coastline and the maritime traffic. Indeed, the results showed a 65 % decrease in the litter recovery rate (*RR*) between pre-lockdown and post-lockdown (Table 3). At a post-lockdown stage, each boat would bring to port an average of 20 (± 12) items per day. In addition, based on this recovery rate, two scenarios were designed considering different levels of fishing boats involvement over a year. The first scenario considers an active participation of those boats that have cooperated with the project removing litter from the seabed (RRa), meaning that these boats would be collecting litter every working-day simultaneously. In this case, the litter removal in the zone amounts to hundreds of thousands of items each year. The second scenario considers the collaboration of the entire trawling fishing fleet of the Gulf of Cadiz (RRb), which would multiply by 3 the removal of litter. The estimated RR validates the important role that fishing vessels can play against marine litter pollution.

4.4. Pros and cons of artisanal fishing trawling boats of marine litter

This section analyses the benefits and challenges of expanding the collaboration between fishermen and scientists, as an opportunity for mitigation, monitoring and the raise of awareness on marine litter all over the world. In this sense, there are a series of advantages and difficulties that arise from the application of the methodology that should be considered in further implementation.

4.4.1. Advantages

4.4.1.1. Low implementation costs. This methodology is an opportunistic passive sampling, since the main activity of trawlers is fishing. Obtaining data on marine litter is an opportunity for researchers and managers. The major cost lies mainly in hiring personnel in charge of collecting and classifying the waste at port. Involving local fishermen may offset this cost, but the increased tasks and the nature of the tasks may make them reluctant to get involved. Further efforts are related to the preparation of a report using a standardized scrutiny method, which collects both the data related to the sampling (tracking of the vessel, type of network, fishing ground, date, etc.) and that of marine litter itself.

4.4.1.2. Wide spatial and temporal range. The prospect of involving fishing trawlers provides the possibility of covering a wide study area that will change over time, since the boats do not fish in the same area and the catch area changes depending on the target species and/or the time of year. In addition, the possibility of obtaining samples almost daily, during most of the year, allows establishing monitoring strategies able to register seasonal and annual variations related to marine litter. In short, it is possible to evaluate with greater certainty the environmental status of the area studied, with the consequent development of effective measures for the prevention and reduction of waste.

4.4.1.3. Implementation of the methodology in different areas and countries. The expansion of the collaboration to other trawl fishing fleets would allow researchers to assess differences and similarities between different regions. In this way, recommendations and management protocols aimed at reducing and eliminating marine debris could be developed, coordinated between both national and supranational administrations.

4.4.1.4. Validation of the results from oceanographic surveys. Scientific oceanographic campaigns require both technical and personal resources. Due to their high cost, they are not capable of sampling large areas, carrying out long transects or establishing monitoring strategies over time. Oceanographic surveys are often very limited in space and time in relation to the extensive at-sea labour of the fishing sector. The involvement of trawl fishing fleets in seabed monitoring would provide solid support for the scientific analysis of results derived from oceanographic surveys.

4.4.2. Difficulties

4.4.2.1. Persuade the fishermen's association to collaborate. Establishing a marine litter collection protocol can be seen as extra work for sailors without a direct economic benefit. Furthermore, they may reject the idea of being considered as sweepers of the sea. Their involvement implies awareness of the social benefits that their collaboration entails, such as improved public image in the fight against marine litter pollution or clarifying the real provenance of litter, since artisanal fishermen are often accused of polluting marine waters with fishing gear.

4.4.2.2. Control over the sampling protocol. There is little control over the sampling, since the fishermen are the ones who carry it out. There may be cases in which the waste from different hauls is not separated or the waste generated on the ship is mixed with the waste collected on the bottom. To avoid this, the crew must become aware of the importance of their role in the sampling process, together with training in the basic notions of the sampling protocol (that must be as easy as possible). In short, those ships where there is full confidence in the marine litter data collection system must be considered.

4.4.2.3. The size of litter. The size of the litter retrieved will depend on the mesh size. Most of the artisanal trawl fisheries use nets with 3–4 cm mesh size, meaning that despite the fact that 2 cm litter could be retrieved (as it happened in this study) macro-litter will tend to be bigger than 4 cm. This deviates from traditional definition of macro-litter and it needs to be considered within comparison purposes.

4.4.2.4. Confidentiality of tracking data. Currently, the geolocation and tracking of the fishing vessels is confidential and owned by the Spanish administrations. Moreover, fishermen could be reluctant to reveal their fishing areas. This might be a limiting factor.

4.4.2.5. Closed seasons for fishing. Trawlers might not be allowed to go fishing during periods when moratoria on fishing are in force. This implies that for those weeks it is not possible to obtain marine litter data by them.

4.4.2.6. Insufficient number of samples (hauls). Artisanal fishing trawling boat may not work homogeneously throughout the analysed area. This could cause the sampling effort to be non-uniform, generating more sampled areas than others. This fact may lead to greater variability in litter concentrations, especially in the short term. One option could be to carry out sampling at those points where the number of hauls is insufficient. Another option could be to maintain an extended collaboration over time, as this would provide a better temporal and spatial litter trends in the seabed.

4.4.2.7. Overfishing for litter. Whitin a monitoring context, there might rise a concern related to the removal of litter by the trawlers that could lead to a decrease of recorded items over time. However, this situation is not likely to happen unless a combination of factors occur, including: a) limited area cover such as harbours, b) an enormous sampling effort, determined by a high number of trawlers and high frequency of sampling for litter, which would imply the absence of regulations and quotas in the area.

5. Conclusions

The results obtained in this study show that (1) interannual trend in litter concentrations was associated to the global health emergency derived from COVID-19 pandemic, with a progressive reduction in seafloor litter from 2019 to 2021. (2) Litter pollution on the nearshore seafloor of the Gulf of Cadiz demonstrated an intense anthropic activity related to a heterogeneous use (occupational and recreational) of both waters and shores, together with some litter coming from maritime and fishing activities further offshore. (3) Plastic was the main marine litter material, with single-use items and those related with fishing activity being the most frequent objects. (4) Averaged litter concentration and composition were not subject to significant seasonal variability, but the location of litter hotspots on the seafloor moved with the seasons. (5) It is important to note that the present data are result of a passive sampling opportunity derived from trawl fishing activity. The methodology presented low implementation and development costs, with a wide spatial and temporal sampling range, offering a tremendous mitigation strategy if expanded to the overall bottom-trawling fleet. (6) If applicable in other areas, it would be possible to assess the environmental status with greater certainty, and thus develop monitoring strategies that would allow the development of plans for the prevention and reduction of marine litter.

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CRediT authorship contribution statement

Josué Viejo: Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Andrés Cózar:** Methodology, Writing – review & editing, Supervision. **Rocio Quintana:** Data curation, Writing – review & editing. **Elisa Martí:** Investigation, Writing – review & editing. **Gorka Markelain:** Investigation. **Remedios Cabrera-Castro:** Writing – review & editing, Resources, Project administration, Funding acquisition. **Gonzalo M. Arroyo:** Writing – review & editing, Resources, Project administration, Funding acquisition. **Enrique Montero:** Methodology, Investigation, Resources. **Carmen Morales-Caselles:** Conceptualization, Methodology, Validation, Investigation, Resources, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The datasets generated for this study can be found in www.marinelitterblab.eu

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Appendix A. Supplementary data

Including Fig. S1, Fig. S2, Fig. S4 and Fig. S4. Summary of datasets generated for this study that including calculations of item densities based on distance to shore and number of items per category. Supplementary data to this article can be found online at doi:https://doi.org/10.1016/j.marpolbul.2023.114882.

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