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Baseline

Benthic litter in fishing grounds of the Northern Adriatic: Role of the trawling fleet as cleaners of the seafloor

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ABSTRACT

This study represents the baseline of estimation of the potential service provided by fishermen as "cleaners of the sea". The amount, composition and depth distribution of marine litter in fishing grounds of the Northern Adriatic seafloor has been investigated through the fishing for litter (FFL) scheme. Passive FFL campaigns were carried out by trawlers from two of the most important fishing ports in the northern Adriatic, Chioggia and Goro, from May 2020 to May 2021. Over the course of 256 days of fishing, over 6 tons of litter were removed from 265 km^2 of seafloor. Abandoned, lost and derelict fishing gears (ALDFG) were the most represented litter category (48 % of the total litter), and of these 67 % were plastic ALDFG (mostly mussel socks and fishing nets). Fouling on plastic waste was analyzed to determine the fraction of collected litter items that could be destinated to recycling. Only a small percentage of the plastic litter analyzed was "clean" from adherent and/or encrusting organisms. Approximately 2.4 tons of plastic were recovered, but, due to the biological colonization of surfaces, they cannot be recycled by using the technologies present in the area.

Marine litter is a concern around the globe, and no oceanic region is known to be immune to this threat (Galgani et al., 2000; Cózar et al., 2015; Soares et al., 2020). The Mediterranean Sea is particularly exposed to marine litter pollution: it is an extremely busy sea, it receives continental waters from catchment areas of three continents, its coastline is highly anthropized and a popular tourist destination, and, finally, its semi-enclosed nature limits marine litter dispersion to other ocean areas (Liubartseva et al., 2016). Among Mediterranean regions, the Adriatic Sea seems to be particularly vulnerable to the accumulation of marine litter (Schmid et al., 2021, and references herein) owing to its geomorphological characteristics and anthropic pressures such as aquaculture, fishing, port activities, seaside tourism, heavy maritime traffic, and river outflow that drain the highly densely inhabited, industrialized, and intensively cultivated areas of northern Italy (Atwood et al., 2019).

Seafloor and beaches are, in most cases, the last destinations of marine litter (Canals et al., 2021; Vlachogianni, 2022). The litter on the seafloor of fishing grounds inevitably ends up entangled in the nets of bottom trawlers. Fishing industry could play a primary role in the removal of marine litter from the seafloor as the fishermen, rather than throwing the litter back into the sea, can keep it on board and dump it properly on land. As a matter of fact, Fishing for Litter (FFL) was originally developed with the commitment of KIMO International in the North Sea (www.fishingforlitter.org) with the aim to reduce marine litter by involving the fishing industry. FFL pilot schemes were then implemented particularly in the North Sea (Wyles et al., 2019). FFL schemes can be passive or active. The passive scheme involves the collection of marine litter during normal fishing activity without any financial incentives, while the active scheme involves targeted campaigns to collect waste in specific areas and be paid for it (UNEP, 2015). In the Mediterranean Sea, the only program that adopted the FFL pilot schemes was the DeFishGear (Derelict Fishing Gear Management System in the Adriatic Region; Vlachogianni et al., 2017), through which an assessment of the amount and composition of marine litter was carried out in areas of the Adriatic and Ionian Seas (Vlachogianni et al., 2018; Fortibuoni et al., 2019). A recent study highlighted that Italians were convinced about the contribution of FFL schemes to reduce marine litter (Forleo and Romagnoli, 2023), however, except for activities carried out within the framework of research programs like DeFishGear, FFL was not applicable to Italian seas: the legislation in force until June 2022 (DLgs 152/2006, 2006) specified that marine litter collected from the sea should be classified as "special solid waste" and transportation

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without legal documents should be considered as "illegal waste trade", thus making fishermen liable to prosecution. As a consequence, all the marine litter collected during fishing activities by the Italian fishing fleet of any category has always been thrown back into the sea.

To reduce the amount of marine litter in the environment, a series of actions are needed (Willis et al., 2018), ranging from the removal of litter already present to the improvement of litter management on land, to the improvement of the recyclability of products (a circular economy approach), to the involvement of those who work at sea in actions that help remove litter already present in the sea. This baseline paper summarizes the results of a research program aimed at: i) investigating the amount, composition and distribution of marine litter in fishing grounds of the Northern Adriatic seafloor, ii) evaluating the potential role of a professional trawling fleet as a "cleaning service" for the seafloor, iii) testing different types of land management for marine litter disposal, iv) assessing the type and amount of fouling attached to plastic litter. The latter information becomes relevant in a circular economy perspective, when it is understood to what extent collected litter is recyclable.

Passive FFL campaigns were carried out by trawlers from two of the most important fishing ports in the northern Adriatic, Chioggia (45°13.195′N, 12°16.765′E) and Goro (44°50.999′N, 12°17.508′E). 15 stern trawlers participated to the research program, for a total amount of 256 days of fishing, from 7th May 2020 to 28th May 2021. Litter collection was performed by means of bottom two-panel trawls, and each survey consisted of a day/work (18 h) of bottom trawling, during which each stern trawler carried out, on average, 4 hauls. Hauls lasted 3 h each. For each trawl, geographical position and depth were recorded (Supplementary Material 1). The swept area was calculated using the horizontal opening of the net (20 m) and the distance trawled for each haul:

$$\text{Surface }(\text{km}^2) = [\text{distance }(\text{m})^{*}\text{ horizontal opening }(\text{m})\,]/10^6$$

Distance was obtained from the mean speed of the boat (i.e., 2.8 knots during trawls) and the time of the haul:

$$\text{Distance }(\text{m}) = \text{speed }(\text{miles/h})^{*}\text{ time }(\text{h})^{*}\text{ }1852$$

The swept area was used to calculate the amount of litter items on bottom area (i.e. kg km^{-2}).

Once on board, litter items contained in the catch were separated from fish and other organisms (sea stars, sea urchins, etc.), identified and weighted (precision: 1 kg), and placed into bags. A form was filled out with the categories of litter and the relative weight. Categories, following Keller et al. (2010), were: plastic, metal, wood, and ALDFG (abandoned, lost or discarded fishing gears). ALDFG were further divided into categories: mussel socks, trawl and gillnets, pots, ropes, metal cables and frames, the latter being used in the "rapido" fishery, a type of bottom trawling practiced in the northern Adriatic for scallops and flatfish (Pranovi et al., 2000). Once in port, the bags were taken to the reception facilities with the exception of wood which, after being quantified, was thrown overboard (with the risk, albeit minimal, of being caught again in subsequent trawls).

Considering that, for the reason stated above, both ports lack adequate port reception facilities for the marine litter delivered by fishing vessels, two different types of land management were adopted. At the Chioggia port, there were already roll-off containers located near the fish market and used for the waste from the market itself, and the fishermen who participated in the study were given permission to place the collected litter in those containers. Instead, at the Goro port a collaboration was stipulated with the Municipality of Goro and CLARA, the company entrusted with the civil waste management service, which positioned special bins on the quays and was responsible for disposal in its plants.

Finally, filled forms were collected by the scientific staff, who randomly checked the correctness of the procedure and subsampled the plastic litter fraction for laboratory analysis. Here, the amount of fouling present on a subsample of 80 plastic items, representative of types of plastic waste recovered, was analyzed. Given the different categories of plastic items considered (nets, socks, foils and containers), the analysis was performed using 3 fouling categories: i) clean (no visible fouling), ii) slightly fouled (visible fouling on <20 % of the litter surface), iii) fouled (fouling visible on over 20 % of the litter surface). Fouling organisms were then observed under a Nikon SMZ-745 T microscope for taxonomic identification. The taxa present as single individuals (e.g. Polychaetes, Molluscs) were recognized and counted, while other taxa (algae, gelatinous or colonial organisms) were categorized as: i) absent, ii) present (patches on the item ≤3), and iii) common (patches on the item >3).

6139.7 kg of litter were collected, for a total of about 265 km^2 of seafloor trawled. Fig. 1 shows some examples of litter caught, while Table 1 reports the amount of litter caught at each depth interval. Due to the depth characteristics of the North Adriatic basin, the number of trawls had an unbalanced distribution by depth intervals. Excluding wood, the average amount (±S.D.) of litter recovered was 13.4 ± 19 kg km^{-2}. Overall, the most represented litter category was ALDFG (Fig. 2), with an average amount (±S.D.) of 11.0 ± 16.1 kg km^{-2}, followed by wood (8.1 ± 14.8 kg km^{-2}), plastic (4.1 ± 5.3 kg km^{-2}), and metal (0.5 ± 3.4 kg km^2). The wood was mainly natural (e.g. branches), but some artifacts (e.g. pallets) were also found. Non-ALDFG plastics were mainly containers, disposable bottles and cups, foils from packaging, food wrappers, and other items like shreds of footwear and soles. Non-ALDFG metal was constituted by cans, food related items (e.g. aluminum wrappers), pieces of household appliances, and even a gas cylinder.

Starting from the georeferenced sampling points, a geostatistical interpolation was performed in GIS environment to map the collected data. The interpolation algorithm adopted was the Inverse Distance Weighting, which estimates values at unsampled points by weighting the surrounding data by the inverse of the squared distance from the sampled points. The results are the map of the estimated distribution (in kg) of marine litter and ALDFG in the study area (Fig. 3). As shown by the map, the area is not totally available for trawling, owing to off-shore mussel farming plants along the entire coast, platforms for gas extraction in the southern area, an LNG terminal for gas tankers in front of the Po Delta, and scattered organogenic formations on the seafloor (the so-called "tegnùe") in the northern part. From the maps, a decreasing pattern in the amount of litter and ALDFG can be observed moving off from the coast, with an exception in the off-shore north-eastern quadrant where the amount of ALDFG on the seafloor is remarkable.

Differences in the bathymetric distribution of marine litter (4 depth intervals: 10–20, 20–30, 30–40, 40–50 m) were investigated through permutational multivariate analysis of variance (PERMANOVA) (Anderson et al., 2008), using Euclidean distance resemblance measure. Null hypothesis assumed no bathymetric differences in litter abundance and composition. PERMANOVA highlighted significant differences (p < 0.0001; df = 3, 255) in the bathymetric distribution of the amount of marine litter recovered. The paired comparisons (Supplementary Material 2) highlighted some significant differences between the different depth intervals within each category of marine litter, with the exception of non-ALDFG metal, which was distributed quite homogeneously. Although 3 times more samples were taken at these depths than at others, the fact remains that in the 20–30 m depth interval significantly greater quantities of plastic ALDFG and wood were found. Metal ALDFG was significantly present in greater quantities in the 30–40 m interval, a probable indication of the fact that the "rapido" fishing is carried out at those depths.

The composition and abundance of fouling organisms differed among the different plastic items. Only a small percentage of the marine litter analyzed was "clean" from adherent and/or encrusting organisms, probably a function of the length of time spent in the water. Probably due to the greater surface available for adhesion due to their three-dimensional shape, socks and nets were the items most colonized by fouling organisms (Fig. 4). Excluding algae and Tunicates, all fouling organisms produce calcareous tubes or shells: in this way, the plastic

Fig. 1. Examples of marine litter.

Table 1
Number of trawls and mean weight ± S.D. (kg km^{-2}) of the categories collected at each depth interval.

Depth	Trawls	ALDFG		Plastic		Metal		Wood	
M	N	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
10–20	48	2.9	5.8	2.8	4.5	0.4	2.6	3.5	5.2
20–30	157	11.9	18.0	5.1	5.9	0.5	3.9	10.3	17.1
30–40	45	16.5	15.0	2.5	2.7	0.6	2.4	6.7	12.8
40–50	6	12.7	6.6	1.8	3.6	0.2	0.4	0.5	16.2

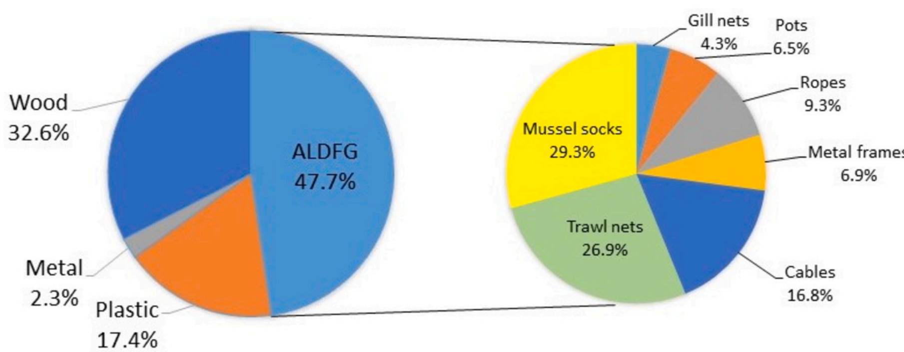

Fig. 2. Percentage based on the total weight of marine litter belonging to the different categories collected; details of ALDFG's subcategories are given.

marine litter is very rich in calcareous encrustations. Table 2 shows the frequencies of the taxa found: the most common organisms were tube worms (Serpulidae) and bivalve molluscs (Mytilidae and Ostreidae).

Over the course of 256 days of fishing, 15 stern trawlers removed over 6000 kg of waste from the seafloor. This is an important amount of litter if compared to other Mediterranean fishing grounds: along the Catalan coast, for example, only 349.4 kg of marine litter were removed from 305 hauls (Balcells et al., 2023). Despite the rivers that discharge their waste content (Munari et al., 2021), and anything that can fall or be intentionally thrown overboard by crews/passengers from the large number of ships that ply this stretch of sea (www.marinetraffic.com), this study highlights that the marine litter present in greatest quantity derives from professional fishing activities and mussel farming (i.e. ALDFG). In the area investigated the mussel *Mytilus galloprovincialis* is farmed on a total area of over 4000 ha, in off-shore plants with long-line suspended farming systems. Mussel socks (3–5 m long), which contain 50–70 kg of mussels each, are tied to the long-line at regular intervals (50–80 cm). During the life cycle of the mussel, the socks are replaced three times as the molluscs grow and increase in size, and, since the operation is carried out "on-site", it may happen that socks are dispersed at sea due to accidents (or to the carelessness of farmers). From a recent study, however, the main cause of the loss of socks seems to be violent storm surges: it has been estimated that the storm surge of November 2017 caused the loss of about 50,000 mussel socks in that area (Mistri and Munari, 2019).

The results of this study shows that the direct involvement and empowerment of fishermen is an efficient way to collect marine litter through passive FFL, as the litter present on the seafloor constitutes a significant by-product of daily capture. If instead of throwing it back into the sea, fishermen have the opportunity to dispose of it safely and without costs on land, the result is a direct removal of litter from the seafloor without need of a specific cleaning action. To do this, fishermen i) do not have to endure inconveniences due to litter storage on board, ii) must be able to dispose of the litter easily once they return to port, iii) should not run the risk of incurring sanctions or fines during this activity. The stern trawlers of the Goro and Chioggia fleets have limited

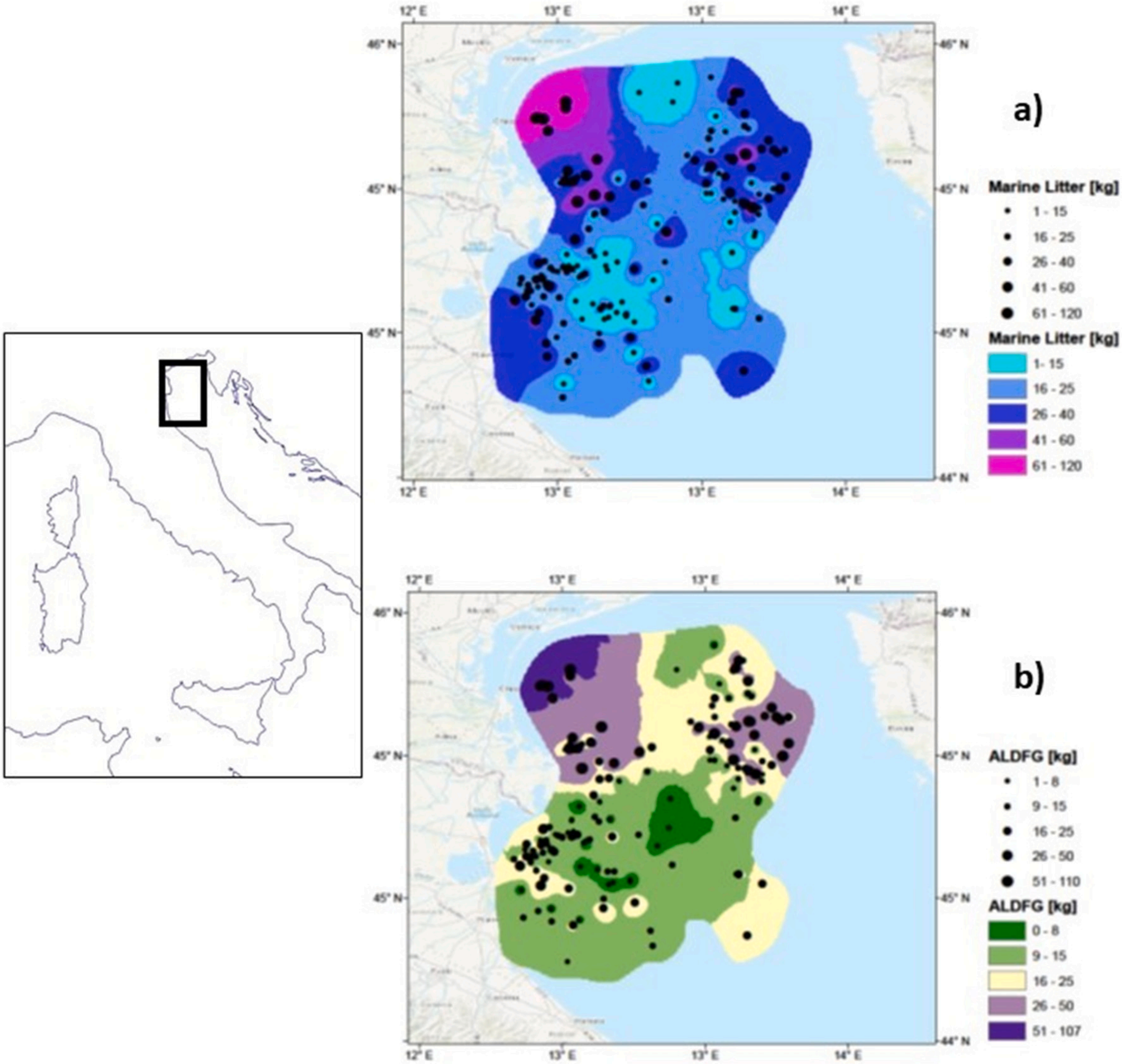

Fig. 3. Distribution of a) marine litter, and b) ALDFG in the study area.

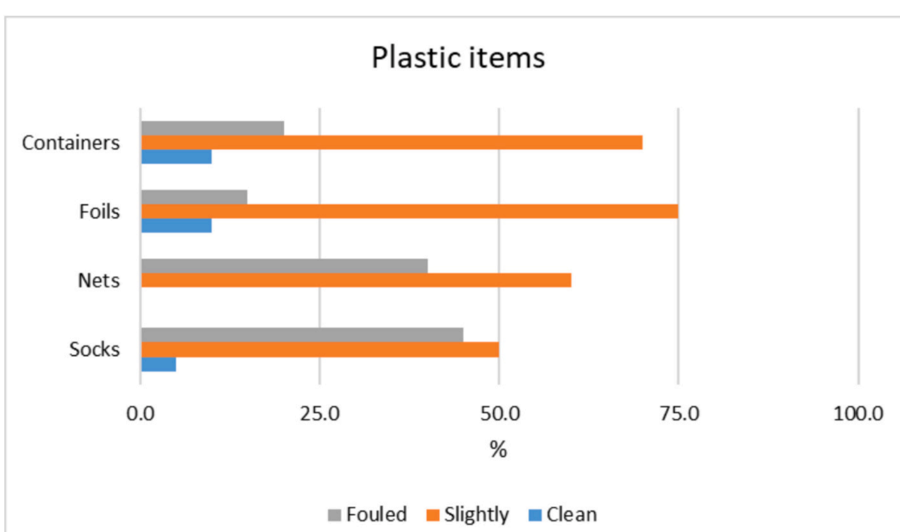

Fig. 4. Colonization of different plastic items by fouling organisms.

Table 2
Fouling abundance on 4 different types of plastic items (x: present; xx: common).

	Socks	Nets	Foils	Containers
Mucilage	xx	xx	xx	xx
Green algae indet.	xx	x		
Red algae indet.	xx	x		
Colonial Bryozoa indet.	x	x	xx	xx
Sprirobranchus triqueter	301	177		
Pileolaria sp.	199	39	15	
Spirorbis sp.	214	145	16	7
Vermiliopsis sp.	44		4	9
Hydroides sp.	70			
Serpula sp.				11
Mytilus galloprovincialis	112			
Anomia ephippium	27	9		
Crassostrea gigas	18			
Ostreola parenzani	14	3		
Sepia officinalis eggs		12		
Ascidiacea indet.	xx	xx		

dimensions (overall length 12–18 m), and fishing campaigns rarely last more than one day, after which vessels return to port to land the catch. For this study, fishermen were provided with bags (50 L volume) in which to sort and store the litter, but the limited waste storage capacity on board influenced the amount and type of litter disposed, since wood, once caught and registered on the form, was thrown overboard. Although the wood collected was mainly classified as "tree branches - tree trunks" (only rarely there were recognizable fragments of wooden planks), all wood was considered as litter since the current Italian legislation for the disposal of wood (DLgs 152/2006, 2006) classifies wood waste (including uprooted or felled trees) as non-hazardous special waste (establishing the methods of management, transportation and disposal). The outflow of major rivers (Isonzo, Tagliamento, Piave, Adige, Po, Reno) on the western side of the Adriatic provides an explanation for the amount of wood (over 8 kg km^{-2}) carried to the sea during floods (Tesi et al., 2008). Concerning port reception facilities, we found different responses from the 2 fleets. The roll-off containers present at Chioggia, positioned to serve the fish market, were several hundred meters away from the mooring of the stern trawlers, and fishermen had to spend extra time and effort to dispose of the bags in the roll-off containers. Furthermore, any type of waste is thrown into the containers, and therefore the sorting of the litter carried out on board was lost. At Goro the case was different: the local company CLARA set up 6 "ecological oases" for the separate disposal of the marine litter on the quay, only a few meters from the mooring of the fishing vessels. Each oasis was equipped with 2 separate 1000 L-containers, one for the plastic waste, and another for "other waste", so the sorting of plastic on board was maintained. In 2019 the EU institutions adopted the new Directive on Port Reception Facilities (PRF Directive 2019/883) for the delivery of waste from ships, in which "passively fished waste" is included as a new waste category (defined as passively fished waste, or waste collected in nets during fishing operations). The PRF Directive was implemented in Italy only in 2022 (beyond the end of our research program), through the Salvamare (Save-the-sea) Decree (DLgs 60/2022, 2022), which, among other things, decriminalized the transport and landing of waste collected during fishing activities. Unfortunately, most Italian ports, particularly the smaller ones, still lack adequate port facilities for the disposal of the passively fished waste. The fleet operating in the northern Adriatic Sea (approximately 2900 vessels) accounts for 24.6 % in numerical terms of the entire Italian fishing fleet (CREA, 2023). The contribution that this fleet could make to the removal of waste from the sea is thus enormous, once the port reception facilities for the "passively fished waste", like those tested at the port of Goro, are implemented in all Adriatic ports.

Plastic ALDFG constituted approximately 50 % of the litter caught (Supplementary Material 1). A large number of recycling technologies are available for plastic, including mechanical and chemical options (Schwarz et al., 2021). However, changes in the characteristics of plastic marine litter caused by biodegradation and thermo-oxidative degradation cause problems during plastic waste processing, and affect the properties of products made from recycled plastic (Gere and Czigány, 2018). Moreover, considering marine litter, standard mechanical recycling methods are ineffective and economically unsustainable because plastics litter is mixed, contaminated by salts and incrusted with organic matter, shells, tubes, algae, etc. As a matter of fact, the majority (about 94 %) of the plastic waste recovered in this study could not be sent for recycling due to extensive colonization by fouling organisms (Fig. 4). Among the available technologies, pyrolysis provides a promising way to upcycle marine plastic waste (Faussone and Cecchi, 2022). However, industrial-scale pyrolysis plants for the chemical recycling of plastic waste are practically absent in Italy. Versalis, Eni's chemical company, has begun the construction of a demo plant in Mantua in 2023. According to correct waste management implemented by EU Directive 2008/98, strategies for plastic litter include energy recovery technologies as an alternative to recycling, given that landfill and disposal (most adopted in Italy) are cheaper but less sustainable for the environment and human health. When recycling is difficult due to the high degradation of the materials, energy recovery may be the most sustainable solution (Bertling and Nühlen, 2019). Waste-to-energy technology exploits the combustible properties of plastic and the possibility of burning the latter together with municipal solid waste to produce thermal or electrical energy. At the moment, given the lack of other large scale industrial plants, this seems in the short to medium term the only viable solution to the problem of plastic marine litter disposal in Italy (and probably also elsewhere).

This study represents the "baseline" of estimation of the potential service provided by fishermen as "cleaners of the sea". It fills a gap of information in scientific literature, especially in Italy, where the legislative pathway for allowing fishermen to carry litter onboard has been arduous and is yet to be completed. If on the one hand Adriatic fishermen may be important seafloor cleaners, on the other hand it is necessary to recognize the commitment of fishermen and their role, both ethically (e.g. by introducing a logo for the "cleaners of the sea"), and practically (e.g. by providing preferential access to public tender for adaptation of fishing equipment) way. As a matter of fact, the decrease in marine litter on the seafloor constitutes an advantage for the fishermen, as the risk of damaging the nets is lower, for the (Adriatic) beaches, by benefitting the Municipalities and entrepreneurs who are in charge of cleaning the beaches, for tourists (who are not exposed to beached waste), and for the marine ecosystem as a whole. The intense fishing and aquaculture activities in the Northern Adriatic produce large quantities of plastic litter. Plastic socks, nets, etc. become immediately and heavily colonized by a whole series of organisms, many of which have tubes or calcareous shells, which make recycling difficult, except through advanced industrial processes currently not present in the area. Thermal valorization seems, at the moment, the most sustainable solution for plastic marine litter.

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CRediT authorship contribution statement

Michele Mistri: Writing – original draft, Validation, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Elia Casoni:** Formal analysis, Data curation. **Virginia Strati:** Formal analysis, Data curation. **Cristina Munari:** Writing – original draft, Validation, Methodology, Formal analysis, Data curation.

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. The funder had no role in the design of

the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Data availability

Data are in Supplementary Material

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