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How to Deal With Seafloor Marine Litter: An Overview of the State-of-the-Art and Future Perspectives

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Marine litter is a significant and growing pollutant in the oceans. In recent years, the number of studies and initiatives trying to assess and tackle the global threat of marine litter has grown exponentially. Most of these studies, when considering macro-litter, focus on floating or stranded litter, whereas there is less information available about marine litter on the seabed. The aim of this article is to give an overview of the current state-of-the-art methods to address the issue of seafloor macro-litter pollution. The overview includes the following topics: the monitoring of macro-litter on the seafloor, the identification of possible litter accumulation hot spots on the seafloor through numerical models, and seafloor litter management approaches (from removal protocols to recycling processes). The article briefly analyzes the different approaches to involve stakeholders, since the marine litter topic is strongly related to the societal engagement. Finally, attempting to answer to all the critical aspects highlighted in the overview, the article highlights the need of innovative multi-level solutions to induce a change toward sustainable practices, transforming a problem into a real circular economy opportunity.

Keywords: marine litter, seafloor litter, derelict fishing gear, marine litter mapping, numerical modeling, pyrolysis, circular economy, stakeholder engagement

INTRODUCTION

Marine debris is a growing problem with plastics making up 60–80% of marine litter worldwide (Derraik, 2002). Plastic enters in the sea as macro- (>0.5 cm) and micro- (<0.5 cm) litter. In the marine environment several chemical and physical processes affect its shape, density, and composition (Zhang, 2017; Guo and Wang, 2019; Schwarz et al., 2019). The global amount of plastic entering the oceans each year is estimated to be between 4 and 12 million metric tons (Jambeck et al., 2015). The five ocean gyres, i.e., North and South Pacific, North and South Atlantic, and Indian have been identified as the largest accumulation zones together with highly populated, shallow, and enclosed waters, such as the Mediterranean Sea (Cózar et al., 2015; Suaria et al., 2016).

Marine litter can be found throughout the marine environment, i.e., the beach, sea surface, water column, seafloor as well as on and in marine biota. Much of the research on distribution, accumulation zones, and concentrations of marine litter have focused on beach and floating litter, while studies on benthic litter are more problematic due to the less accessible environment

(Galgani, 2015; Schneider et al., 2018; Schwarz et al., 2019). However, investigating the seafloor is of fundamental importance, as it is estimated that about 70% of marine debris sinks to the seabed with unknown consequences (UNEP, 2005). Even low density polymers can lose buoyancy under the weight of bio-fouling. Deposition rates on the seabed depend on many factors, such as the size and density of plastic objects, depth, currents, wave motion, and the topography of the seabed.

Marine litter has physical, chemical, and biological implications, as well as economical ones (McIlgorm et al., 2011; Raynaud, 2014; Brouwer et al., 2015; Newman et al., 2015; Watkins et al., 2015; Vlachogianni, 2017). Impacts of marine litter on marine organisms were reported on 557 species, showing the deleterious effects and consequences of entanglement, consumption, and smothering (Secretariat of the Convention on Biological Diversity and the Scientific and Technical Advisory Panel—GEF, 2012). Although marine birds, turtles, and mammals have received most attention, the effects on other organisms, such as fish and invertebrates, are becoming more evident. Ingestion of floating waste and entanglement in discarded or lost fishing gear and ropes might have consequences on survival capability of an individual, often causing direct mortality (Kühn et al., 2015). Yet, there are also sub-lethal effects on organisms that result in reduced energy intake, which may influence fecundity rates. Plastics contain and adsorb persistent organic pollutants (POPs) (Rios et al., 2007). POPs not only pose a problem for the marine environment but can bio-accumulate through the food web and affect human health (Gobas et al., 2009). Recently, plastic pollution has become so pervasive that new mixtures of melted plastic and natural sediments or rocks (the so-called plastiglomerates and plasticrusts) have been discovered (Corcoran et al., 2014; Gestoso et al., 2019).

The sources of marine litter can be grouped in two broad categories: land-based and marine-based sources. Land-based sources include landfills and littering of beaches and coastal areas (tourism), rivers and floodwaters, industrial emissions, discharge from storm water drains and untreated municipal sewerage (UNEP, 2009). It is estimated that land-based sources contribute substantially to the marine litter problem, about 80% of the total (STAP, 2011). Marine-based sources include cargo and passenger shipping, recreational boating, military navigation, fishing and aquaculture facilities, and the energy industry, as well as legal and illegal dumping (Čulin and Bielić, 2016). The importance of marine-based sources can greatly vary in different regions: in the Northeast Atlantic, maritime activities such as shipping, fishing, and offshore installations, together with coastal tourism activities, are the predominant sources (OSPAR, 2009). Not all sectors produce the same amount of marine litter. For instance, tourist ships have been identified as one of the principal pollution sources of marine eco-systems with cruisers being a particular problem (Allsopp et al., 2005; Jeftic et al., 2005).

Fisheries and aquaculture related activities are another marine-based sector that produces marine litter. Abandoned, lost or otherwise discarded fishing gear (ALDFG) is thought to contribute approximately 10% of the marine litter deposited at sea per year (Macfadyen et al., 2009; Pham et al., 2014). However, this amount can greatly vary depending on the importance of local fishing and aquaculture activities and on specific hydrological and geomorphological conditions (Pham et al., 2014). In the Pacific garbage patch, ALDFG is considered to contribute nearly half of the tonnage found in the region (Lebreton et al., 2018; Richardson et al., 2019). Similarly, derelict fishing gear was the prevalent type of litter on the seafloor of the upper São Vicente submarine canyon (SW Portugal), representing 89% of total debris (Oliveira et al., 2015). Within the Mediterranean Sea, Angiolillo et al. (2015) reported that, in the deep seafloor of 26 areas off the coast of three Italian regions in the Tyrrhenian Sea, the dominant type of debris (89%) was represented by fishing gears (mainly lines). The most abundant quantities were observed on rocky banks in Sicily and Campania, which are characterized by intense recreational and professional fishing activities. The durability and morphology of ALDFG imply that when it sinks, it often snags on reefs and on other underwater obstacles causing significant damage to benthic habitats, impacting ecosystems and fisheries through "ghost fishing" and acting as a navigational hazard (Richardson et al., 2019).

Information on the characterization, quantification, and location of the amounts of marine litter also represents the background for the development of the management strategies to reduce marine litter and to verify their effectiveness. The management measures proposed and then adopted to tackle the environmental problems related to marine litter are divided into three categories: (a) preventive measures to avoid the occurrence by reducing the sources (e.g., waste reuse and recycling, waste conversion into energy, enforcement of port reception facilities, gear marking); (b) mitigating measures to reduce the presence and the impacts through debris disposal and dumping regulations; (c) curative measures to remove litter from the marine environment through clean up campaigns and retrieval programs (Chen, 2015). Measures to raise awareness are also essential to lead to behavioral changes in citizens and stakeholders. These management measures are contained in a number of policy instruments (e.g., conventions, regulations, and strategies) proposed at global, regional, and European Union (EU) levels, both compulsory and voluntary. The legislative framework refers to two main sectors: the protection of the sea and its resources, including the fishery sector, and the waste management (**Table 1**).

The most important global conventions were negotiated under the United Nations Environment Program (UNEP) and the Agency for the Safety, Security and Environmental Performance of International Shipping (International Maritime Organization, IMO). According to their different nature, these instruments were explicitly transposed into regional or EU legislation or served as guidelines for the states to take coordinated actions to tackle the marine litter issue. The EU has recently developed a European Strategy for Plastics and the follow-up legislation to reduce the negative effects on the environment of some single use plastic items and derelict fishing gear. In 2019, the EU adopted the long-awaited Directive 2019/904/EU on the reduction of the impact of certain plastic products on the environment, which introduces several bans and restrictions on different uses and materials. This

TABLE 1 | List of the main strategies and regulations developed to address marine litter issue at international, regional, and EU levels.

Level	Main sector	Instruments	Provisions related to marine litter and derelict fishing gear
Global instruments	Environment protection	United Nations Convention on the Law of the Sea (UNCLOS, 1982)	Sets the adoption of all the necessary measures to prevent, reduce and control any type of pollution in order to protect and preserve the marine environment
		UN Fish Stocks Agreement, 1995	Promotes the development of environmentally safe fishing gear and techniques to protect fish stock and to minimize impacts by lost or abandoned fishing gear
	Fishery	Code of Conduct for Responsible Fishing, 1995	Sets universal standards and principles to guide governments and private actors for a sustainable use of aquatic resources and for responsible fishing practices, directly referring also to ALDFG
	Waste management	The International Convention for the Prevention of Pollution from Ships (MARPOL 73/78), 1973-1978	Annex V sets measures to eliminate or reduce the amount of garbage and solid waste produced by ships and discharged into the sea, and sets the absolute prohibition of the disposal of plastic waste into the sea
		London Convention and 1996 Protocol	Sets the complete stop of waste dumping at sea, represents a decisive change in the approach to the question of the use of the sea as a deposit of waste materials and introduces the so-called "precautionary approach" and the "polluter-pays principle".
Mediterranean Region instruments	Environment protection	Barcelona Convention 1976 and Protocols	Aims to protect the Mediterranean Sea against pollution. Dumping protocol: prevention and elimination of pollution by dumping from ships and aircraft or incineration at sea. LBS Protocol: protection against pollution from land-based sources and activities
		Barcelona Convention: Regional Plan on Marine Litter Management in the Mediterranean (2014)	Aims to prevent and reduce to the minimum marine litter pollution in the Mediterranean and its impact on ecosystem services, habitats, species (in particular the endangered species), public health and safety and to remove to the extent possible already existent marine litter. The plan also intends to implement the « fishing for litter » system.
		MEDPOL program (1996): Strategic Action Program for the management of marine litter in the Mediterranean, 2011	Aims to minimize and further eliminate, to the fullest possible extent, marine litter in the Mediterranean Region through regional and national activities. The Strategy highlights that marine litter represents a local, national as well as trans-boundary problem needing specific measures at each level and across all levels,
European instruments	Environment protection	Marine Strategy Framework Directive (Directive 2008/56/CE) and the subsequent Commission Decisions (2010/477/EC and 2017/848/EC)	Descriptor 10: Properties and quantities of marine litter (macro and micro) do not cause harm to the coastal and marine environment, also including marine organisms, in particular referring to ingestion of and entanglement in litter and derelict fishing gear
	Environment protection	The European Strategy for the Adriatic and Ionian Region (EUSAIR), 2014	Specific objective within the Pillar 3 "Environmental quality" is to improve waste management by reducing waste flows to the sea. The foreseen actions to contrast pollution at sea include to joint efforts to deal with entire life cycle of marine litter.
	Fishery	Regulation (EC) 1224/2009 for a Community control system and its Commission Implementing Regulation (EC) 404/2011	Specifies mandatory measures to the marking and identification of fishing vessels and of fishing gear used in community waters and the correct behavior to adopt when fishing gear is lost during fishing operations, emphasizing the obligation of a timely retrieval or, if the lost gear cannot be retrieved, of a detailed notification to the competent authorities
		Regulation (EC) 1005/2008 establishing a Community system to prevent, deter and eliminate illegal, unreported and unregulated fishing	Illegal fishing is recognized as one of the most serious threat to the sustainable exploitation of aquatic resources and to marine biodiversity. As well as one of the causes that led to the abandonment of fishing gear at sea.
	Waste Management	Waste Framework Directive (Directive 2008/98/EC)	Although not directly related to the management of ship-generated or fishing waste or to marine litter, the Directive offers a modernized framework and establishes a five-step waste hierarchy approach where prevention is the best option, followed by re-use, recycling and other forms of recovery, with disposal such as landfill as the last option.
		Directive (EU) 2018/851 amending the Directive 2008/98/EC	Specifically refers to marine litter recognized as a particularly pressing problem, and states that measures should be taken to halt the generation of marine litter particular from land-based activities
		Directive (EU) 2019/883 on port reception facilities for the delivery of waste from ships, repealing the Directive 2000/59/EC	Introduces some important novelties: the inclusion, among the waste from ships covered by the Directive, also of "passively fished waste", defined as waste collected in nets during fishing operations; encourages the use of 'fishing for litter schemes' and provides that the costs of collection and treatment of passively fished waste are not borne exclusively by port users
		Directive (EU) 2019/904 on the reduction of the impact of certain plastic products on the environment	Introduces several bans and restrictions on different uses and materials. This initiative focused on the ten most found single use plastics and on fishing gear containing plastic and set limits on the use of single use plastics through a national reduction in consumption, design and labeling requirements, and waste management/clean-up obligations for producers are also specified

initiative focused on the ten most found single use plastics and on fishing gear containing plastic.

The purpose of this paper is to give an overview of the most recent advances with regards to seafloor macro-litter pollution, from monitoring and assessment to prevention and mitigation. The review covers the following topics: (**Figure 1**): (1) the assessment of macro-litter on the seafloor including the monitoring and the identification of possible

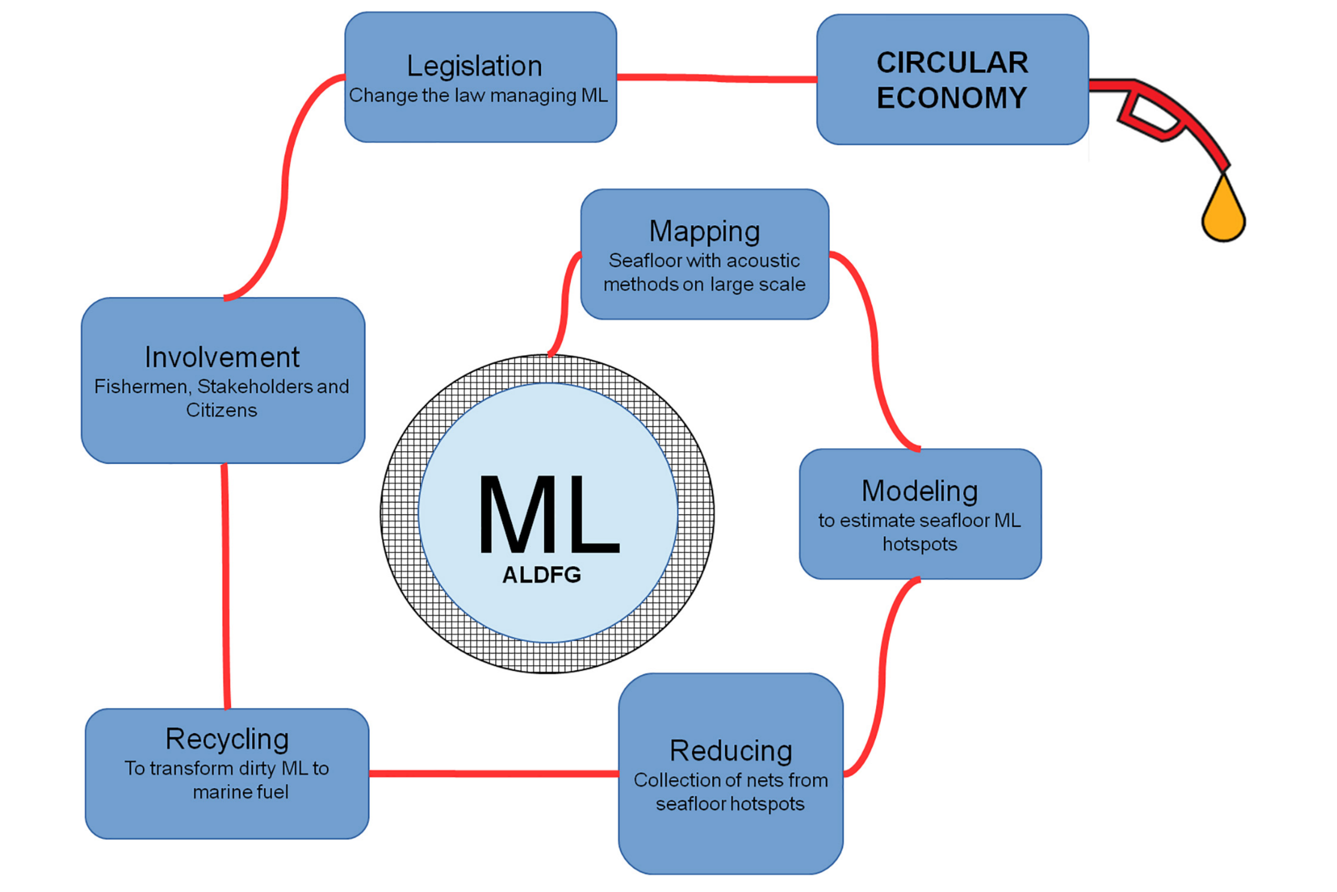

FIGURE 1 | Conceptual model illustrating the main actions needed to tackle the marine litter issue.

litter accumulation hot spots through numerical models; (2) the management of seafloor marine litter, including the removal and recycling procedures, and the strategies for stakeholder and citizen engagement.

Finally, attempting to answer all the critical aspects highlighted in the overview, in the future perspectives we suggest a holistic approach, combining actions to tackle the phenomenon of marine litter at all phases, from reduction and prevention, through the monitoring and quantification up to the removal and recycling. This multidisciplinary approach aims to avoid, prevent, or mitigate environmental, economic, and social losses derived from poor marine litter management practices.

ASSESSMENT OF MACRO-LITTER ON THE SEAFLOOR

Monitoring the Presence of Macro-Litter on the Seafloor

The detection and characterization of marine litter on the seafloor relies mainly on three different approaches (or sometimes a combination of them): litter collection with bottom trawlers, optical mapping, and, more recently, acoustic mapping of the seafloor.

Trawling for scientific purposes allowed extensive investigation of large areas of the seafloor and monitoring of marine litter over long periods of time. For example, Maes et al. (2018), present the results of a long term monitoring of the North West European seas investigating a wide inshore (within 12 nm of land) and offshore (>12 nm) area of the Celtic and Greater North Seas (2461 trawls). Gerigny et al. (2019) analyses a 24-year time series of data based on trawling for fish stock assessment of the MEDITS project in a large area of the French Mediterranean continental shelf. A similar approach has been recently adopted for other parts of the Mediterranean Sea (e.g., Galgani et al., 2013; Pasquini et al., 2016; Fortibuoni et al., 2019; Spedicato et al., 2019). However, bottom trawlers present several limitations: (1) they are invasive for the seafloor; (2) they cannot operate on rocky bottom where litter (such as ALDFG) is likely to accumulate; and (3) they do not give precise information about the spatial distribution of the litter on the seafloor.

Optical methods are based on videos and images collected either by divers in shallow coastal and/or coral reef environments (e.g., Donohue et al., 2001; Bauer et al., 2008) or by high resolution cameras installed on Remoted Operated Vehicles (ROVs) (i.e., Oliveira et al., 2015; Gerigny et al., 2019;

Pierdomenico et al., 2019), manned submersibles (Galgani et al., 2000; Watters et al., 2010) or unmanned platforms such as Unmanned Surface Vehicles (USVs) or Autonomous Underwater Vehicles (AUVs) (Wynn et al., 2014; Huvenne et al., 2018) (**Table 2**). Photographic transects were collected also using a towed camera over different years (since 2002) in the HAUSGARTEN observatory in the Fram Strait (Bergmann and Klages, 2012; Tekman et al., 2017) and on the continental shelf or in the deep sea in the Bay of Fundy, Canada (Goodman et al., 2020). These methods are commonly used for quantifying marine litter on the seafloor (e.g., Angiolillo et al., 2015 for a review and the more recent works by Melli et al., 2017; Consoli et al., 2018; and Pierdomenico et al., 2019 in the coastal areas of the Mediterranean Sea) and its increasing presence over time (Tekman et al., 2017).

The advantage of the optical methods is that they are non-invasive, they provide quantitative data and they can be applied to all types of seafloor including complex rocky substrata. From the collected images it is possible to obtain photomosaics of the seafloor combining different video frames. In some cases, thanks to photogrammetry, the images can be used to interpret the 3D morphology of objects in the pictures (see, e.g., Drap et al., 2015 and Price et al., 2019 for photogrammetry applications to corals and archeological remains in deep sea, respectively). This can be achieved either using stereophotographic cameras or combining sufficient overlapping consecutive photographs from a single moving camera (Huvenne et al., 2018). Moreover, the images can also provide useful information about the benthic habitats. Typically, high resolution cameras allow the identification of litter larger than 5 cm.

However, the use of cameras can be limited by the visibility or the hydrodynamic conditions and can only cover points or transects. For example, Angiolillo et al. (2015) used a ROV to cover an area of 6.03 km^2 over 4 months, with an average mapping rate of, i.e., 0.002 km^2/h in average. Melli et al. (2017) mapped some rocky outcrops in the Northern Adriatic Sea using ROV transects covering a total area of 0.039 km^2 with a mapping rate of about 0.0014 km^2/h. With a drifting drop frame camera, Goodman et al. (2020) covered an average area of about 0.002 km^2/h.

More recently, also underwater hyperspectral imaging (UHI) has shown a strong potential of detecting small objects and it has been shown that UHI can be used as a non-invasive, *in situ* taxonomic tool for benthic megafauna with sizes on a sub-cm scale (down to 0.8 cm) with an increased detection rate for small (<2 cm) objects having a resolution of 1 mm/pixel (Dumke et al., 2018; Foglini et al., 2019).

Acoustic methods have considerably improved their efficacy since the first review of the different methods applied for benthic marine litter detection by Spengler and Costa (2008). The use of acoustic methods for waste detection on the seafloor dates back to the early 1990s. Karl et al. (1994) made use of side scan sonar (SSS) and video recording to identify barrels and other containers of low-level radioactive waste dumped on the

TABLE 2 | Examples of different underwater optical and acoustic methodologies reported in recent studies. The mapping rate and the detectable target dimension were estimated, where possible, from the data available in the different studies.

Method		Estimated mapping rate (km^2/h)	Detectable target dimension (m)	Depth (m)	Bottom type	Geographical area	Source
Optical methods	Divers	0.006	<1 m	10 m	Coral reef	Northwestern Hawaiian Islands	Donohue et al., 2001
		0.001-0.004	< 1 m	10–20	Rocky outcrop	North Adriatic Sea	Fiorin, R. (from GHOST project experience)
	Camera mounted on ROV	0.002	<1 cm	30–300	Rocky bottom	Tyrrhenian Sea	Angiolillo et al., 2015
		0.0014	<1 cm	20–30	Rocky outcrop	Northern Adriatic Sea	Melli et al., 2017
	Drifting drop frame	0.002	<10 cm	10–100	From muddy and sandy flat seafloor to bedrock and till	Bay of Fundy, Canada	Goodman et al., 2020
	UHI	0.0001	<0.8	4200	Manganese nodule field	Peru Basin (SE Pacific Ocean)	Dumke et al., 2018
		0.001	<0.8	200–400	Muddy and rocky seafloor	Bari Canyon, Adriatic Sea	Foglini et al., 2019
Acoustical methods	SSS	-	≤10 m	100–2500	-	San Francisco Bay	Chavez and Karl, 1995
		0.125	≤2 m	100–150	Soft mud seafloor	Chiniak Bay, Kodiak Island, Alaska	Stevens et al., 2000
	MBES	0.097–0.728	≤1 m (depending on the distance from seafloor)	2–20	Mostly muddy - sandy mud and rocky outcrops	North Adriatic Sea	marGnet survey - Madricardo et al., 2019
	HRSS	0.012	5 cm	10–20	Rocky outcrop and sandy seafloor	North Adriatic Sea	Fiorin, R. (from GHOST project experience)
	SAS	-	1 cm	-	Various types of seafloor	Extensive survey in different locations-	Williams, 2014
		2.25	4 cm	-	-	Southern Ionian Sea	Zwolak et al., 2020
	FLS	-	<1 cm	-	Sandy seafloor	Tank experiment	Valdenegro-Toro (2016)

continental margin off San Francisco Bay between 1946 and 1970. Chavez and Karl (1995) applied a spatial variability analysis and other digital processing procedures to the SSS images (with 1 m pixel resolution) to automatically detect and map the location of barrels a few meters long on the seafloor. Stevens et al. (2000) employed SSS to locate lost crab pots off Kodiak, Alaska, making use of submersible and ROV to confirm the remote observation.

Identification of the location of mines on the seabed has driven a large number of studies dedicated to underwater target detection using acoustic data and specific dedicated algorithms. Synthetic aperture sonar (SAS) imaging can reach up to 1 cm/pixel resolution and has proven particularly useful for the detection of proud mines on the seabed (Williams, 2014). Recent development of the interferometric SAS mounted on an AUV allowed to reach a specified image resolution better than 5 cm and a mapping rate of 2 km^2/h (Zwolak et al., 2020). SAS data acquired with AUV systems in deep waters in the Norwegian Sea within the MAREANO (Marine areal database for Norwegian waters) program in Norway, demonstrated the effectiveness of mapping also individual coral blocks indicating that this technology could be successfully applied for marine litter surveys (Thorsnes et al., 2020).

The recent development of multibeam echosounder systems (MBES) (Hughes Clarke, 2018) has made it possible to collect georeferenced co-located bathymetry and backscatter intensity data for the mapping of objects with very high spatial resolution. Hughes Clarke et al. (1999) showed the effectiveness of the combined use of side scan sonar imagery and MBES data in the search for aircraft debris after the crash of Swiss Air Flight 111, off Nova Scotia, Canada. Mayer et al. (2007) conducted specific experiments showing that the resolution of multibeam sonar combined with 3D visualization techniques provided realistic looking images of mines and mine-like objects that were dimensionally correct and enabled unambiguous identification on a sandy seafloor. More recently, Madricardo et al. (2019) used high resolution MBES data (up to 5 cm resolution to map objects larger than 0.8 m) to assess the mean abundance of marine macro-litter in a large area of the Venice Lagoon and to identify marine litter hot spots (see **Figure 2a**). The average area *per diem* covered was 0.68 km^2/day with a mapping rate of 0.097 km^2/h (Madricardo et al., 2017).

Valdenegro-Toro (2016) proposed the combined use of Forward-Looking Sonar (FLS), frequently used by AUVs as obstacle avoidance sensor, to detect submerged marine debris and the Convolutional Neural Networks (CNNs) showing the promising results of a tank experiment.

Moschino et al. (2019) present the results of acoustic surveys that were carried out on biogenic rocky outcrops (Northern Adriatic Sea) during the Life GHOST project using a High-Resolution Scanning Sonar head – HRSS. The HRSS provided very detailed images of the seabed near the sonar head (up to 100 m) (**Figure 2b**), highlighting the presence of ALDFG.

The main limitation of the acoustic methods in comparison with images or videos is still resolution which is dependent on the sonar characteristics and the distance from the target.

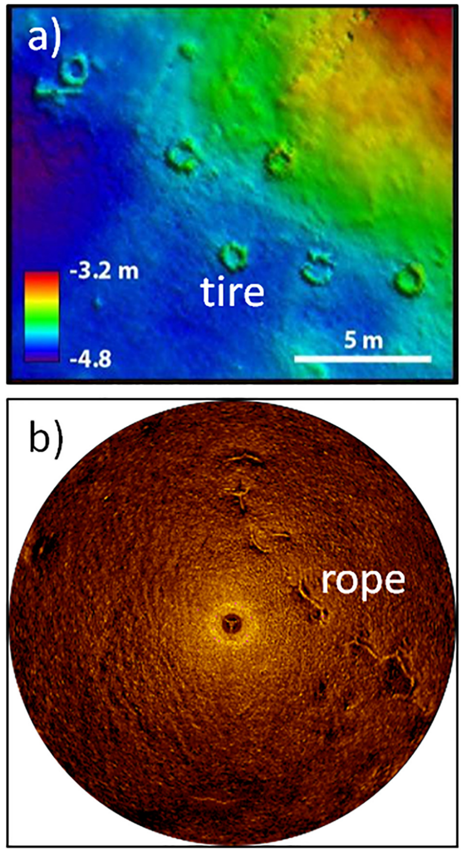

FIGURE 2 | (a) Example of tires on the Venice Lagoon seafloor mapped with a high-resolution MBES (modified from Madricardo et al., 2019). **(b)** Example of rope fragments on the seafloor mapped with HRSS during the "GHOST" project.

To overcome the specific limitations of the non-invasive optical and acoustic methods (i.e., limited coverage and resolution, respectively), the solution seems to be the systematic combination of the two approaches. This will be more readily feasible in light of the rapid development of autonomous vehicles, such as USV and AUV, that are likely to be the future of the marine litter surveys for shallow and deep waters, respectively. We can expect that new levels of autonomy will allow a fleet of USV or AUVs to be launched to survey a specific area. The autonomous vehicles will communicate and co-operate to survey the area in an efficient and safe manner and use machine learning algorithms to compute and analyze high-resolution acoustic data on-the-fly. Then, it will be possible to perform a close-to-bottom photographic survey after identifying key targets for in-depth study (Sture et al., 2018; Thorsnes et al., 2020). This approach is also highlighted by the future integrated marine debris observing system (IMDOS) which has to provide long-term monitoring of the state of anthropogenic pollution and support operational activities to mitigate impacts on the ecosystem and on the safety of maritime activity (Maximenko et al., 2019).

Modeling Litter Dispersion and Fate

Numerical models can be used to predict the fate of litter in the sea and its effect on marine organisms; however, we are still some distance away from developing a fully multi-disciplinary approach, and there are still several gaps in knowledge and model development. Numerical models can integrate and account for the most relevant physical, bio-geochemical, and physiological processes and consider multiple stressors, feedbacks, and accumulation effects. Different model setups can produce a range of scenarios shedding light on the global impact of each process on short-, medium-, and long-term scales. The MODEL plastic workshop identified the water-sediment plastic interaction process as one of the three main knowledge gaps (Martins et al., 2019). The other two are the quantification of point and diffuse sources of plastic and the identification of hot spots of plastic accumulation.

Several studies focus on modeling floating litter at the global (Lebreton et al., 2012; van Sebille et al., 2015; Corral, 2017), Mediterranean and Adriatic scale (Mansui et al., 2015; Liubartseva et al., 2016, 2018; Carlson et al., 2017). Numerical models often estimate the distribution and convergence of floating litter by tracking the particle movement due to currents, wind and waves interacting sometimes with the shoreline. The wind drift routines are often derived from already existing oil spill codes. Some authors developed models with no particle sinking (Yoon et al., 2010; Critchell et al., 2015) or considered the wash ashore effect when particles enter grid cells with a model shoreline (Maximenko et al., 2012). Only a few studies investigate the fate of marine litter taking into account loss by degradation, fragmentation, sinking, ingestion, and bio-fouling. These processes influence the size and the density of the particles changing their pathways in the marine environment. However, these processes are difficult to parameterize accurately.

Only a limited number of studies explicitly focus on macro-litter. Corral (2017) developed a simple routine for degradation/sinking process parameterization. Their model evaluated the global 'plastic cycle', indicating the areas where litter can accumulate with time. The study showed that sinking can occur at multiple sites along shores on the pathway to and from the gyre in the Pacific.

In other cases (Liubartseva et al., 2016), sinking is computed in a statistical way taking into account the age of particles while neglecting particle change of buoyancy and subsurface transport by a 3D current field (Liubartseva et al., 2018). Critchell and Lambrechts (2016) developed a plastic fate model: plastic particles enter the sea as macro-plastic and are directly affected by the wind. Later particles can go through beaching and re-floating, settling, degradation into micro-plastic, and burial in the sediment. No seafloor re-suspension and no return flow from open boundaries are considered. The mathematical treatment of the sinking plastic is the same for both micro and macro plastic using different settling rate coefficients. The sensitivity analysis of the tool offers a useful guide to set-up processes in other models highlighting the overall relevance of the input data in the definition of litter sources.

Jalón-Rojas et al. (2019) developed a numerical model for micro-plastic debris to include all these processes. In addition, they presented a sensitivity analysis of the tools to assess which variables influence the sinking of particles. Their results indicate that plastic density and biofilm thickness and density have the biggest effect on the transport, followed by turbulent dispersion and washing-off.

What is still missing is a description of the relationship between micro- and macro-litter and the water column and seafloor. This aspect is poorly understood and has been neglected for a long time in marine litter modeling. Some studies are starting to consider this aspect (Gutow et al., 2018; Palatinus et al., 2019). Recent results indicate the possible existence of micro-litter fiber carpets on the ocean floor (Woodall et al., 2014; Hardesty et al., 2017) and the relevance of the near-bottom transport for the seafloor litter distribution (Pham et al., 2014).

Gutow et al. (2018) collected floating and seabed macro-litter and investigated their relationship using numerical models without sinking processes and statistical analysis. Their results highlight the relevance of biofouling and of near bottom transport. Palatinus et al. (2019) collected field data of floating macro- and micro-litter and seafloor micro-litter in the Adriatic Sea, along a part of the Croatian coastline. No clear correlation was found between floating macro- and micro-litter or between floating and seabed micro-litter data. This study, together with others in the Mediterranean area (Suaria and Aliani, 2014; Carlson et al., 2017; Fossi et al., 2017), points to the need of an improved understanding of processes and further modeling. To be compared with field data, model results need to be calculated on the basis of a 3D hydrodynamic model with high spatial and temporal resolution. At the same time, the particle tracking model has to take into account the wind drift effect, particle sinking and the subsurface and near bottom transport.

A crucial point in all the numerical approaches is to define the input characteristics in terms of how often, how much and what kind of litter enters in the model. The main sources of litter in the ocean are from land (Hardesty et al., 2017). Several studies estimate the amount and kind of litter on beaches (Vlachogianni et al., 2018) and seabed (Strafella et al., 2015). Lebreton et al. (2012) and Liubartseva et al. (2016) estimate the quantity of floating litter from the main cities, rivers and from shipping lines. Missing in these previous works is the amount of litter deriving from fishing activities and from aquaculture plants.

Another relevant point is that sinking particles are represented as spherical particles with neutral buoyancy. In more complicated studies, particles with asymmetrical length and width sink differently depending on the angle between object and current direction. For this purpose, the paper of Gabitto and Tsouris (2008) looks at the sinking velocity for a cylindrical shaped object, which, one could imagine, approximates the shape of a discarded net if it is rolled up. The results are corroborated with field data and experiments which are in good agreement with the equation in the case of small objects.

MANAGEMENT OF SEAFLOOR MARINE LITTER

Removal of Seafloor Marine Litter

Since marine litter has become a global threat, an increasing number of videos, photos and direct witnesses have showed to the world that fish and benthic organisms were not the only inhabitants of the seafloor. Many removal activities have been planned and implemented all over the world to restore marine habitats and save untold millions of marine organisms (Donohue et al., 2001; Cho, 2011; Szulc et al., 2015; Sahlin and Tjensvoll, 2018; Vlachogianni et al., 2018; Williams and Rangel-Buitrago, 2019). Removal activities may be subdivided into two main categories, retrieval performed by trawling or removal performed through diving surveys. The choice between the two methods depends on the water depth and the substrate characteristics (coherent, as rock or incoherent as mud or sand). On deep soft seafloors, fishing vessels equipped with trawling nets, chains, and chains armed with hooks are used, while on shallow rocky seafloors the scuba and/or snorkel divers are employed. Considering that the two methods are not interchangeable, i.e., fishing vessels cannot trawl on hard bottom and scuba divers cannot reach in safe operative conditions depths below 50 m, they lead to different results, in terms of retrieved material, costs and used technologies. Moreover, removal activities must be carried out only if the resulting environmental benefits exceed the disturbance or damage inevitably caused during removal operations, and only if operations can be performed in a safe and cost-effective way (Da Ros et al., 2016).

Fishermen, as key stakeholders, have been shown to play an important role for the collection of marine litter through the implementation of Fishing for Litter (FfL) activities. These are clean-up actions aimed both at removing litter from the seafloor using fishing vessels and at increasing the awareness of the fishery sector toward the marine litter issue (Ronchi et al., 2019). These FfL schemes are so important that the legislation supports them explicitly (see **Table 1**). FfL activities are commonly divided into two types of practices: active when the removal practices are performed by fishermen during specific funded clean-up campaigns; passive when the litter removal is carried out by fishermen during their normal fishing activities without any financial compensation (KIMO, 2014). The first pilot FfL projects was started in Scotland (UK) in 2005 and was coordinated by KIMO, an association of coastal local authorities whose goal is to eliminate pollution from the Northern Seas (KIMO, 2014). Later on, other FfL campaigns were organized in other Northern European Countries (Sweden, the Netherlands, Denmark. Norway, and Germany), South Korea, the North East Atlantic (OSPAR region), and the Baltic Sea (Ronchi et al., 2019). In the Mediterranean region a number of FfL initiatives were carried out in the framework of EU funded projects such as: DeFishGear[1], ML Repair[2], Plastic Busters[3], and Clean Sea LIFE[4].

Trawling activities, however, are not selective methods, both litters and organisms being collected from the seafloor. Only after the trawls have been completed is it possible to release the caught organisms back into the sea. Most of them, can be damaged and eventually die due to the trawling activity itself. Removal activities carried out by scuba divers may be more accurate, since operations can be performed manually or using scissors and cutters thus preserving marine organisms. However, only a limited amount of materials can be retrieved. Operative depths, visibility, and currents are the main issues for scuba or snorkel divers. Moreover, human safety must be considered in these types of activities. Retrieval activities performed by scuba or snorkel divers may be cheaper in terms of fuel consumption and technologies used and are, without doubt, more respectful of the environment. However, they are more expensive in terms of man hours (Riccato et al., 2016).

A removal protocol for divers, specifically designed for ALDFG entangled on rocky outcrops, was implemented during LIFE GHOST project[5]. The protocol was conceived and developed to be applied in a simply and univocal way, helping the researches step by step considering dichotomous choices. It considers human safety, biota safeguarding, with particular interest on protected species and habitats, and environmental pollution. Two subsequent schemes illustrate the procedure to be followed (**Figure 3**): the first scheme aims to identify the type of ALDFG and materials (**Figure 3A**). The second scheme leads the decision-makers to the final choice of removing or not removing the identified nets (**Figure 3B**) (Da Ros et al., 2016; Moschino et al., 2019).

The newest research approaches focus on implementing automatic or remotely controlled wireless devices capable of collecting plastics and other marine litter in order to conjugate accuracy and sustainability of clean-up interventions also in deep environments[6].

Removal strategies are curative measures and have always to be considered less effective than avoiding debris dispersal into the marine environment. The long-term efficacy of clean-up campaigns is not always guaranteed by the lack of legislative, economic, and infrastructural tools (Ronchi et al., 2019). However, the information they provide on marine litter sources, amounts, and impacts can be used to develop preventive measures (Richardson et al., 2019).

Recycling of Marine Litter

According to the "waste hierarchy" implemented within EU Directive 2008/98 (summarized in **Table 1**), proper management strategies for plastic waste should include recycling (mechanical and chemical) and energy recovery technologies. Landfill disposal, the cheapest but also less sustainable method for the environment and human health, should therefore be the last option to consider[7].

Mechanical recycling includes a series of steps: collection, sorting, washing, grinding, and extruding of the plastic waste, which is transformed into raw materials or secondary products without a substantial change in its chemical structure. Chemical recycling, instead, converts plastics into monomers, oligomers, and higher hydrocarbons using specific solvents (solvolysis), or thermic methods (pyrolysis), with the final aim of obtaining fuels and no-fossil alternative molecules (Ragaert et al., 2017). Waste-to-energy technologies allow to turning non-recycled plastic

[1] http://www.defishgear.net/
[2] http://www.ml-repair.eu/it
[3] http://plasticbusters.unisi.it/
[4] https://cleansealife.it/
[5] www.life-ghost.eu
[6] http://rozaliaproject.org/about/technology/
[7] https://ec.europa.eu/environment/waste/framework/

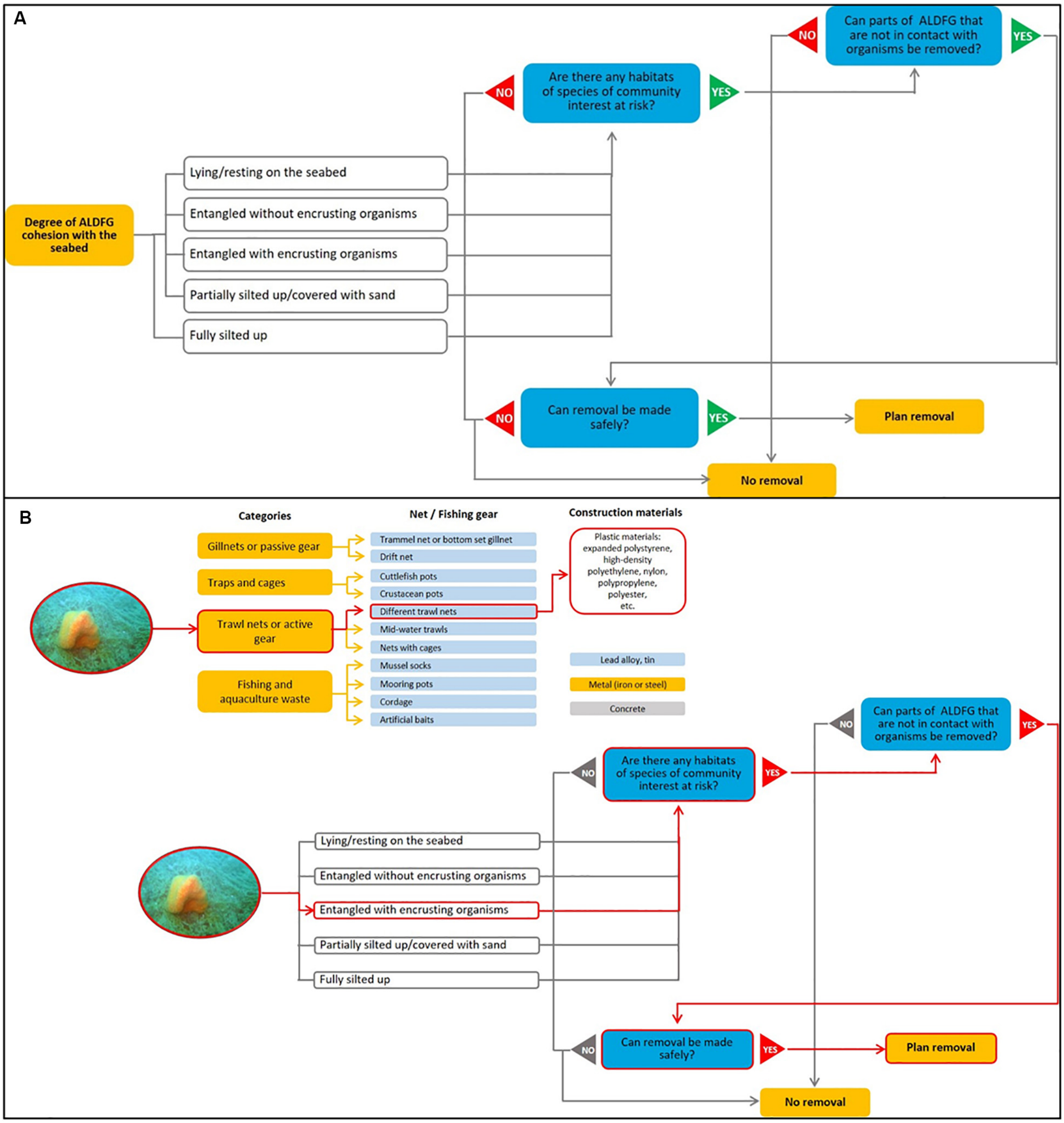

FIGURE 3 | (A) Decision flowchart for assessing the degree of entanglement and removability of ALDFG detected on the seabed. **(B)** Example of application with a bottom trawl to be removed, on which encrusting organism had grown (from Da Ros et al., 2016).

to oil, which can be used to power homes and businesses (Eriksson and Finnveden, 2009).

Worldwide consolidated entrepreneurial experiences were implemented in recent years in the management of plastic materials, especially those aimed at recycling disused nylon 6 fishing nets. Through mechanical recycling processes these materials are converted in various types of products such as accessories, sportswear, textile flooring which have contributed to the economic and image success of many companies (Charter et al., 2018).

However, considering marine litter, standard mechanical recycling methods are ineffective and uneconomical because plastics debris is mixed, contaminated by salts and incrusted with organic matter. From previous experience on marine litter management, it was found that incineration is the method most widely employed to treat marine debris (Iñiguez et al., 2016). Despite some examples where marine litter has been used to manufacture new objects, the magnitude of the marine litter problem requires similar magnitude solutions. Besides, the new objects manufactured from reclaimed marine litter will end up again as waste again sooner or later. If incineration and landfill are the most frequent options for marine litter once recovered from the seas and oceans, then there is little value in recovering it. Yet, there is increasing attention directed toward the synthesis of liquid fuels and chemicals from waste streams in order to reduce the carbon footprint of transportation sectors within a circular economy concept.

Pyrolysis of plastic waste generates a liquid oil (pyrolysis oil) which is composed of several hydrocarbon families, ranging from C7 to C30 + , similar to those of fossil crude oil (Buekens, 2006). Huge amounts of fuel are used globally every year for marine transportation: 207 Mton in 2017 (Fuels Europe, 2019), and huge amount of plastics waste is stranded in landfills and dispersed in the oceans. Therefore, recycling marine litter to produce liquid fuels for marine transportation seems an ideal solution to the problem.

Numerous papers have been published on the pyrolysis of plastic, where the pyrolysis oil can be used as a fossil fuel substitute or as a crude oil replacement (e.g., Buekens and Huang, 1998; Aguado et al., 2006; Blazsó, 2006). Few cases of large-scale applications are documented in the literature and none where marine litter is the feedstock. However, previous works have shown that it is possible to manufacture fuels meeting international ISO 8217 standards for marine fuels by mean of pyrolysis of post-consumer plastic waste (Faussone, 2018) at a relatively large scale of 10 ton/day range. Even ultra-low sulfur fuels can be produced from waste plastics for terrestrial transportation by pyrolysis and hydrogenation as upgrading step (Bezergianni et al., 2017).

Planning Stakeholder Engagement Tools

Effective solutions to prevent or mitigate the presence and the impacts of marine litter require a transition toward a more sustainable way of producing and consuming. With this aim, coordinated actions must be undertaken by several stakeholders involved in different sectors (Lohr et al., 2017; European Commission, 2019). This implies the active involvement of consumers, producers, policy makers, managers, citizens, tourists, fishery industries, companies, and many others. The stakeholder engagement requires a series of actions aimed at designing and organizing the most appropriate participatory process for each category (Walton et al., 2013). The final aim is to promote their participation and active involvement in the decision-making process. In this way, the possible conflicts between the different actors may be solved and the definition of operational solutions is obtained thanks to the contribution of all the actors, leading to a more willing attitude to use the newly implemented systems (Hartley et al., 2015a). Specific involvement strategies were implemented to achieve long-term improving results for marine environment (**Table 3**).

The fishing community naturally finds itself on the frontline of the fight against marine litter. Most of professional fishermen are aware that litter can impact the marine environment by damaging ecosystems and marine animals, including commercial species. They are also conscious that a significant portion of marine litter derives from fishing activities (Wyles et al., 2019).

Therefore, promoting the participation and the active involvement of both fishermen and aquaculture farmers in the fishing waste management process is a prerequisite not only for the long-term prevention of ghost nets and other marine litter but also for optimizing the recovery of discarded fishing nets and the other marine waste (Ronchi et al., 2019).

Policy makers, waste management companies and industries may play a crucial role in outlining a virtuous management system for marine litter, identifying appropriate options for their recovery, disposal and recycling according to the Circular Economy model and the waste hierarchy, with a view to maximizing the environmental benefits. Regular collaborative

TABLE 3 | Management actions to induce a change in the perceptions and attitudes of the different stakeholder groups.

Stakeholder categories	Actions	Examples	Measure
Fishermen and aquaculture farmers	Signing voluntary agreements of responsible fishing	Adopting national codes of practice or guidance, delivering the FAO Code of Conduct for Responsible Fisheries	Preventive
	Improvement of waste management practices	Installing waste containers in fishing vessels to dispose waste generated on board or collected during the fishing activity.	Preventive
	Participation in fishing for litter campaigns	Fishing for Litter scheme: -fishermen collect marine litter during their fishing activity without any financial incentive -fishermen collect marine debris during organized and funded campaigns at sea	Curative
	Participation in education program	Training programs to raise awareness of the impacts of fishing activities on marine biodiversity Training programs for the protection of cetaceans, marine turtles and seabirds.	Preventive
Local and national authorities, Waste companies	Improvement of waste management practices.	Enforcement of disposal collection points for civil wastes and fishing related materials (number and periodicity of collection).	Preventive
Industries	Implement new production chains.	Setting up of mechanical and/or chemical recycling process using marine litter.	Curative
Citizens, students, teachers	Increase awareness on marine litter issue and induce habit change.	Organization of seminars, events	Preventive
		Realization of informative materials	
		Implement specific education programs for students	
		Implement Arts and Science programs	
		Participation in clean up campaigns	Curative
	Support to scientific research activities.	Participation in citizen science programs	Preventive

partnerships between fishers, scientists and managers constitute the most effective way to access local ecological knowledge in fisheries assessment and management (Orensanz et al., 2015; Barnett et al., 2016). At European level, cooperation with fishery sector has allowed decision makers to put in place specific practical solutions aimed at removing marine litter from the sea, improving the waste management practices on-board and port disposal mechanisms with the final aim being to increase recycling process (NOWPAP MERRAC, 2015; Mengo, 2017).

Finally, also citizens may play an important role in triggering processes which may be effective in the fight against marine litter by: paying attention to a proper waste disposal, choosing sustainable certified products, reducing the amount of disposable waste and avoiding the excess of packaging and plastics. To achieve these goals, specific involvement strategies have been applied in order to educate citizens on the importance of the ocean following the Ocean Literacy principles (Santoro et al., 2017), to develop specific education programs for children and students (Hartley et al., 2015b), organizing clean up campaigns or participating in citizen science programs (Hidalgo-Ruz and Thiel, 2015). Art can also give a crucial contribution, reworking the information in the light of the artist sensitivity and creativity. Evocative art works can capture the attention of people and induce them to question their unsustainable habits (Ellison et al., 2018).

FUTURE PERSPECTIVE: THE IMPLEMENTATION OF THE MULTI-LEVEL SOLUTION APPROACH

This work has given an overview of various strategies proposed for the monitoring and management of seafloor marine litter. This section of the article presents a multi-level solution to overcome some of the bottle necks highlighted in the overview:

- A combined underwater acoustic and video remote sensing approach should be adopted to efficiently map wide areas of the seafloor to identify marine litter hot spots. In these hot spots, video footage of the seafloor should be collected either by ROVs, drop frame camera or by divers to ground truth the acoustic data and to increase resolution where needed. Field experiments have been specifically designed to extract the acoustic signature of the various types of marine litter, both in the water column (**Figure 4**) and on different types of seafloor, with focus on

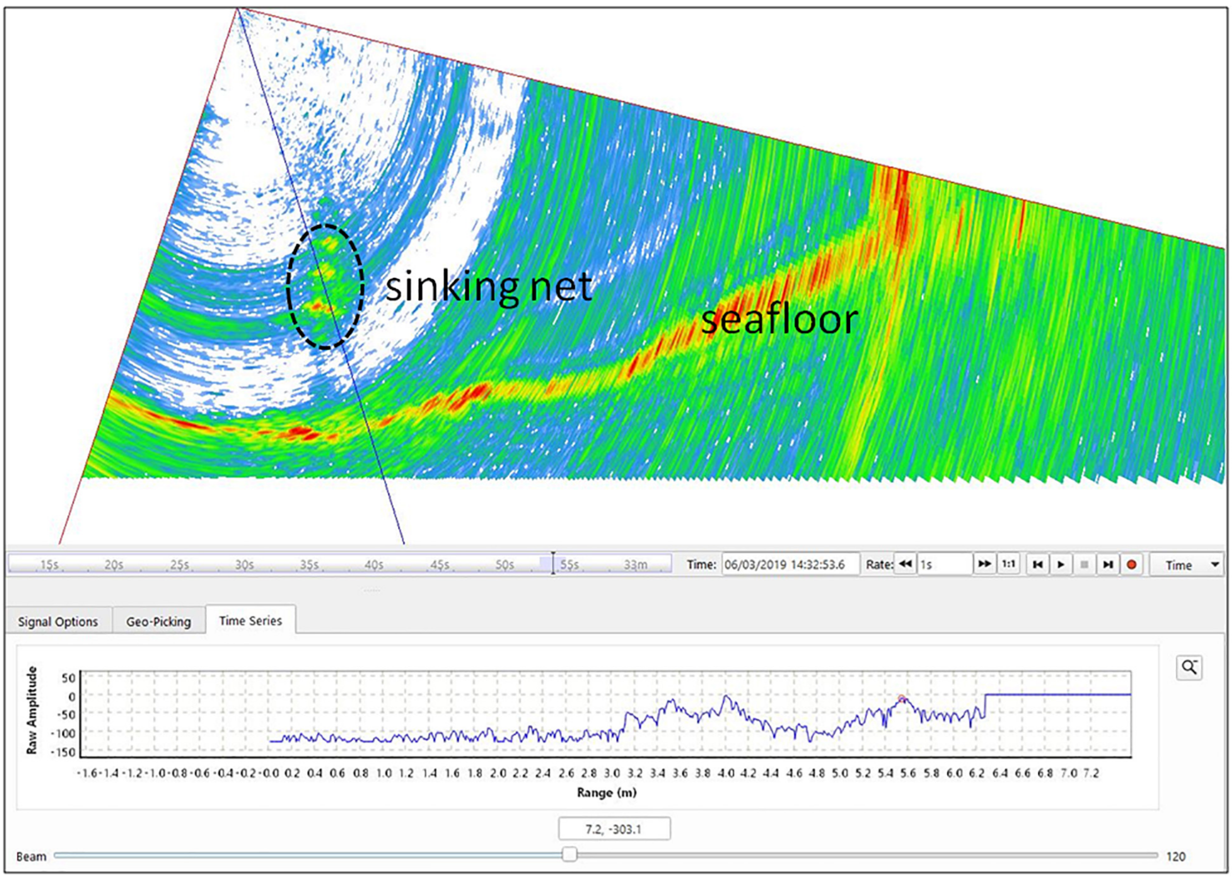

FIGURE 4 | MBES water column data collected to measure the marine litter sinking velocity and acoustic signature and echogram of signal extracted in correspondence of the blue line to identify the sinking net.

ghost nets. Also, the sinking velocities of different marine litter types can be measured to provide a parameter for the numerical modeling. Dedicated target identification algorithms need to be implemented to map and recognize as many categories of benthic marine litter as possible.

- A state-of-the-art Lagrangian model, taking into account sinking speeds based on previous works (Takagi et al., 2007; Gabitto and Tsouris, 2008; Monroy et al., 2017; Tang et al., 2018) should be further developed. The model will have to use input velocities provided from simulations performed using a regional ocean model. Moreover, specific parameterizations need to be developed to represent the sinking process of various types of litter and discarded fishing nets. The aim would be to estimate the trajectories of marine litter and thus identify potential hot spots to be incorporated in coastal zone management and maritime spatial planning strategies.
- The protocols developed during the GHOST project need to be improved and adapted to different geographical locations and substrates. The environmental benefits obtained from the removal actions need to be verified taking into consideration the characteristics of the specific species of fauna and flora populating the investigated areas. Finally, the removal of gear associated with different types of fishing techniques need to be incorporated into the removal protocols, such as long-line gear (100 m of nylon armed nets with hooks lost or discarded on the seafloor).
- Besides the monitoring and removing of the marine litter on the seafloor, there is a strong need to find new solutions to recycling it, giving the limitations of mechanical recycling, or dumping. In this sense the use of marine litter to synthetize liquid fuels for marine transportation seems to be an ideal solution to the problem. New research is ongoing to design fully portable prototypes based on a pyrolysis reactor with a total condensation system and a distillation apparatus that replicate the process of fuel synthesis employed in larger industrial units. Several conditions will have to be fulfilled: (a) fuel quality must comply with technological standards; (b) environmental impact must be in line with regulations; and (c) the equipment must be easy to operate in any context. Use of low temperature pyrolysis for the synthesis of marine fuels will motivate marine litter removal and collection.
- Demonstration days could be organized, targeting fisheries and aquaculture operators and local administrators engaged in the management of marine litter. These public events will show the advantage of collecting marine litter to be transformed into marine fuels to raise awareness and engage fishermen, aquaculture operators and local authorities in a real circular economy process.

CONCLUSION

This article presents an overview of the state of the art methods to deal with seafloor macro-litter pollution which include the monitoring of its presence on the seafloor, modeling its dispersion and fate, and the management strategies to prevent and mitigate its impact. The overview aims to provide a holistic framework to deal with this global challenge while identifying current gaps in the knowledge and presenting future perspectives.

In light of this approach, we believe that a multi-level solution need to be employed which puts in place a chain of actions dealing with the sea-floor litter from the assessment of its distribution, mapping hotspots, to its removal and finally to its transformation into an energy source. This means of obtaining viable marine fuel will then encourage fishermen and citizens to collect and deliver marine litter creating a circular economy process. This way, the proposed solution will transform a problem into an opportunity which could ultimately lead to a change in the perception and the behavior of stakeholders and a change in the legislation concerning marine litter.

AUTHOR CONTRIBUTIONS

FM collected the contributions from the different authors, prepared the section "Monitoring the Presence of Macro-Litter on the Seafloor," **Table 2** and **Figure 2**, and overviewed and edited the full document. MG wrote most of the section "Modeling Litter Dispersion and Fate" together with WM and FD, and prepared **Figure 1**. NN wrote the section "Planning Stakeholder Engagement Tools" and prepared **Table 3**. RF and FR wrote the section "Removal of Seafloor Marine Litter" together with NN and contributed to **Figure 3**. GF wrote the section "Recycling of Marine Litter." PM contributed to the section "Introduction." JB contributed to write the section "Planning Stakeholder Engagement Tools." AK and AP contributed to write the section "Monitoring the Presence of Macro-Litter on the Seafloor" and to produce **Figure 4**. VM wrote the section "Introduction," produced **Table 1**, and contributed to the overview of the manuscript. All authors contributed to the sections "Future Perspective: The Implementation of the Multi-Level Solution Approach" and "Conclusion." All authors contributed to the article and approved the submitted version.

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The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.