



Out of sight, but not out of mind: Key issues regarding seafloor macrolitter monitoring

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ARTICLE INFO

Keywords:

Marine litter

Marine debris

Seafloor macrolitter

Marine plastic pollution

Imagery

Ocean monitoring

ABSTRACT

Following a number of meetings devoted to knowledge sharing, identification of key issues, and discussing the best ways to move forward, a wide international expert community is now able to provide recommendations regarding the monitoring of seafloor macrolitter through observation and imaging. As the seafloor constitutes a major sink for marine litter including plastics, it is important to acquire robust and extensive data on litter distribution, abundance, types and size ranges across marine habitats. This should be done through widely agreed, harmonised, and non-destructive methods encompassing advanced technologies. Training and capacity building are essential elements in this endeavour. Both new and legacy imagery are needed to establish baseline assessments and trends. Informing policy-making is indispensable for effective action through upstream and targeted measures, with seafloor macrolitter (and megalitter) being a vital part of the evidence base for global mitigation measures.

1. Background

The seafloor covers around 71 % of the Earth's surface and encompasses a diverse range of ecosystems, from shallow coastal areas to abyssal and hadal zones, which fulfil crucial ecosystem functions such as carbon burial, nutrient cycling, provision of a unique biodiversity and living and non-living resources (Thurber et al., 2014). There is growing evidence that a significant proportion of litter entering the ocean eventually sinks to the seafloor (Zhu et al., 2024; Townsend Harris et al., 2023; Tekman et al., 2022), where it can affect resident biota and break down into smaller entities (Parga Martínez et al., 2020). As plastic pollution receives global attention, leading to the negotiation of a Global Treaty on Plastic Pollution (UNEP, 2022), quantitative assessments are needed to plan and evaluate mitigation actions. This highlights the need of a global ocean monitoring system with harmonised, agreed, comparable methods and data management. Such a system should take a holistic approach, integrating monitoring of the coastal zone, the sea surface layer and the seafloor. However, it should be noted almost seven decades after the first deep-sea dive in 1958, only 0.001 % of the seafloor at depths larger than 200 m—representing 66 % of the global ocean area—have been imaged according to recent estimates (Bell et al., 2025). This gives a clear idea of the magnitude of what we do not know yet about seafloor pollution.

Reliable long-term data on the sources and sinks of litter and the amounts entering and accumulating in the ocean are needed to underpin policy decisions. Within this framework, the seafloor merits particular attention. A global consensus on appropriate methods for assessing seafloor litter is critical, especially since many of these environments remain largely unexplored. Litter on the seafloor is mostly “out-of-sight”, but it should not be “out of mind”!

Monitoring significant areas of the seafloor at the global level will

require the consideration of available resources and will often need to rely on opportunistic and synergistic approaches to data collection [Box 1]. During two scientific workshops held in Catania, Italy (September 2023), and Shanghai, China (October 2024), a group of world-leading experts discussed knowledge gaps, existing approaches, and technical aspects of seafloor macrolitter monitoring, building on the results from an initial triggering workshop in Bremerhaven, Germany, 2018. The group aimed to provide advice on the needs, feasibility, methodologies, potential synergies and data management requirements for global monitoring of seafloor litter.

2. Scope

This perspective addresses the need to inform global policy on macrolitter pollution in the ocean, with the major part being plastic, through the collection of appropriate data across all marine compartments. Ending plastic pollution through effective provisions requires the identification of emission sources, as well as accumulation areas. Systematic data collection and analysis within defined monitoring frameworks helps policymakers to take informed action through large scale assessments and trend analyses. This paper focuses on direct observation and imaging techniques as non-destructive methodologies to quantify seafloor macrolitter (> 2.5 cm in the longest dimension; GESAMP, 2019), rather than bottom trawling, due to its limitations and associated environmental impacts. For litter categorisation and description see Fleet et al. (2021), providing a methodology for the hierarchical organisation of litter categories in a reporting system. The usage of bottom trawling for seafloor litter assessment is beyond the scope of this paper.

The first target (14.1) of the United Nations (UN) Sustainable Development Goal 14 (SDG 14) on the conservation and sustainable use of the oceans, seas and marine resources for sustainable development

Text Box 1

Synergies

There is an urgent need to integrate litter observations from ongoing surveys collecting imagery for biodiversity, habitat or geological assessments. In addition to scientific surveys, the private sector (e.g., oil and gas, offshore wind, submarine cables, exploration expeditions) has been collecting and currently collects imagery as part of their activities. All this seafloor image data could contribute to cost-effective baseline investigations and monitoring programs.

addresses the need to “prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris...” and proposes a “plastic debris density” indicator (United Nations, 2025). Plastic pollution is framed under the UN’s “Ocean emergency” umbrella and has led to a UN resolution for a legally binding instrument to end plastic pollution (UNEA, 2022). As the ultimate sink for much of the litter, including plastics (Thompson et al., 2004), the seafloor is of paramount importance in addressing this need through improved knowledge, monitoring, and targeted action.

The UN plan of Implementation for the Decade of Sustainable Development for Ocean Science (UNESCO, 2025) further stresses the importance of data stewardship. A global data management framework should be based on the principles of Findability, accessibility, Interoperability and Reusability (FAIR). However, a recent analysis shows that in many cases, these principles are not yet applied (Jenkins et al., 2022).

3. Implementation

3.1. Site selection and survey strategy

Site selection and strategy for new seafloor surveys should respond to critical questions and goals, among which can be:

- Assessment of the damage/loss caused to the natural seafloor and vulnerable habitats.
- Magnitude of litter accumulations and the characterization of litter types and sources.
- Connection with water column and near-bottom processes including those driven by human activities, such as bottom trawling.
- Links with massive litter-release events like tsunamis hitting the coastline,
- Identification of litter input and accumulation trends.
- Identification of litter hotspots wherever they are.

The design of surveys to obtain seafloor litter data is largely driven by constraints such as sea conditions, distance from shore, depth and seafloor morphology, while practical feasibility will depend on availability of survey ships, positioning systems, platforms and imaging tools. Such surveys will likely be combined with other goals and should profit from synergetic approaches. General guidelines should be followed when designing a survey to quantify the abundance and distribution of seafloor litter at appropriate scales. These should include criteria for site selection, minimum area/distance to be surveyed, and the replication levels required for reliable litter abundance estimates.

Existing guidance for monitoring of seafloor litter may require more harmonisation efforts from the technical viewpoint (MSFD TG ML, 2023; GESAMP, 2019).

Building on individual studies, which often are depth range, habitat or region specific, the overall surveying strategy should encompass different depth ranges, with the long-term objective of producing data from a variety of habitats and regions including potential accumulation areas (Buhl-Mortensen and Buhl-Mortensen, 2017), as illustrated by Martynova et al. (2024) in the Red Sea and by Kouvara et al. in the Mediterranean Sea (Kouvara et al., 2025). The shallow seafloor observation approach can involve participatory science (Consoli et al., 2020; Consoli, 2024; Sciutleri et al., 2024). Spatial coverage of surveys should be maximised to enable representative results in line with the survey objective. Pinpointing litter hotspots involves giving priority to areas acting as preferential conduits and depositional sites. Submarine canyons, for example, carry large amounts of plastic and land-based litter to greater depths (Pierdomenico et al., 2019; Dominguez-Carri6 et al., 2020). Abandoned, lost or discarded fishing gear (ALDFG) is particularly common on rocky outcrops and seamounts (Pham et al., 2013; Amon et al., 2020; Angiolillo et al., 2021; Duncan et al., 2023) and, like other megalitter, requires a dedicated survey strategy. But other less-known settings, including deep basins, should not be overlooked (Woodall

et al., 2014; Amon et al., 2020; Hanke et al., 2025). The use of harmonised sampling approaches is critical to produce comparable datasets on litter abundance and characteristics. Modelling of marine litter dynamics to predict and better understand deep seafloor accumulation areas could be useful but would require larger sets of robust data on deep ocean currents and litter behaviour beforehand, to improve model resolution.

3.2. Platform selection

Beyond shallow areas, typically <30 m, accessible by visual observation during SCUBA (Self-contained Underwater Breathing Apparatus) diving, the acquisition of litter imagery from deeper environments requires the use of specialized platforms. These include Remotely Operated Vehicles (ROVs), Autonomous Underwater Vehicles (AUVs), Human Occupied Vehicles (HOVs) and Towed Underwater Cameras (TUCs), with a wide range of capabilities and operational depths, which commonly relate to operational costs, as discussed in Canals et al. (2021). Upcoming AUVs can increase observed area size significantly (Benoist et al., 2019). While the use of technologically complex platforms ensures the collection of the required information, their cost restricts their widespread use (Bell et al., 2023). Low-cost alternatives can capture video and still images at a fraction of the cost (e.g., drift-cams, modular imaging and sensor platforms, raspberry pi cameras), enabling monitoring even if resources are limited (Purser et al., 2020; Dominguez-Carri6 et al., 2021; Bell et al., 2022; Novy et al., 2022).

3.3. Image acquisition and surveyed area

The underwater positioning system, platform, cameras and lighting equipment used, affect the accuracy of navigation data and image quality. These factors influence precise item location and the ability of observers to correctly identify litter objects (i.e., minimum size, item characterization, biota interactions) [Box 2], and to quantify the area covered. Platform and camera system selection is key to obtain fit-for-purpose image data (Nakajima et al., 2014). Photogrammetry can also be used to quantify the surveyed areas (Hanke et al., 2025), while sonar and hyperspectral cameras may provide imaging applications for specific purposes (Sandra et al., 2023). See supplementary information for further details.

3.4. Data analysis including Artificial Intelligence

A clear, fit-for-purpose and widely accepted system for identification of litter items, such as the EU Joint List of Litter Categories developed by the European Union (EU) and Regional Sea Conventions (Fleet et al., 2021), must be part of the monitoring and data analysis guidelines. The lack of such a system and the ensuing classification can hamper data comparability, and thus hinder integrative assessments. However, a harmonised approach for large litter items (>50 cm), including ALDFG, still needs to be developed. A list structure that allows the identification and tagging of uncertain litter items found during seafloor surveys within more generic classes would provide more flexibility and improve the list’s usefulness and usage.

As imaging technologies generate large volumes of images that need to be analyzed, evaluated and archived, several image and video analysis software systems have been developed over the last couple of decades, most of which are open source (Schlining and Jacobsen Stout, 2006; Marcon and Purser, 2017; Picheral et al., 2017; Ontrup, 2009; Gomes-Pereira et al., 2016; Langenkämper et al., 2017; Zurowietz et al., 2019; Parga Martínez et al., 2020; Zhao et al., 2025). The implementation of hierarchical catalogues or dictionaries is required for litter identification (Schlining et al., 2013), while recommendations such as the RecoMIA guidelines (Schoening et al., 2016) should be used to increase efficiency in future projects.

Artificial Intelligence, deep learning and neural networks can play a

Text Box 2

Monitoring interactions of biota with litter

The spectrum of possible interactions between marine litter and *biota* is wide, with both harmful effects and opportunistic use of litter by organisms (Mordecai et al., 2011; Pham et al., 2013; Rodríguez and Pham, 2017; Galgani, 2018; Battaglia et al., 2019; Pierdomenico et al., 2019; Amon et al., 2020; Parga Martínez et al., 2020; Santin et al., 2020; Carugati et al., 2021; Song et al., 2021; Angiolillo et al., 2022; Duncan et al., 2023; Barry et al., 2024). However, seafloor litter surveys often do not consider these interactions, which are generally reported anecdotally (Canals et al., 2021), thus making global comparisons challenging. Further, most reviews on species interactions or disturbances caused by litter refer to the Northern Hemisphere, particularly the Mediterranean Sea (Gall and Thompson, 2015; Kühn et al., 2015; de Carvalho-Souza et al., 2018; Anastasopoulou and Fortibuoni, 2019; Angiolillo and Fortibuoni, 2020; Angiolillo et al., 2021). In a recent critical review of litter-fauna interactions focusing in submarine canyons, Bruemmer et al. (2023) emphasised the importance of standardised data collection and terminology globally to ease global trend assessments and the long-term ecological impacts of marine litter.

key role in video analyses, but these tools are not yet widely used to identify marine litter (Ma et al., 2023; Belcher et al., 2023). Machine learning (ML) offers a solution, but is still hampered by a lack of data standardization and training datasets (Katija et al., 2022). Further development is therefore needed before large scale application of automated analysis can be implemented. Image annotation through collaborative analysis involving citizens is in use for marine seafloor biodiversity assessments (Matabos et al., 2025) and could be also applicable to seafloor litter. Open-source image databases with labelled training data are needed to promote the use of ML tools in marine litter monitoring. The sharing of geo-referenced marine litter images within the wider oceanographic community is strongly encouraged to rapidly advance these technologies.

3.5. Data reporting and archiving

A long-term sustainable database infrastructure is needed to enable data storage and access for multiple uses. This could be a federated system based on regional data hubs, as advocated for by the Global Ocean Observing System GOOS, and following the example of the surface ocean microplastics community, which develops the Global Atlas of Ocean Microplastics, AOMI (Japanese Ministry of Environment, 2025), in close collaboration with EMODnet, the European Marine Observation and Data Network in Europe, and NOAA NCEI, National Oceanographic and Atmospheric Administration in the US. In Europe, the need to develop a collection system to compile all data for monitoring under the Marine Strategy Framework Directive (MSFD) was recognised early (Galgani et al., 2013; Molina Jack et al., 2019). A comprehensive data management system will require further efforts to harmonize existing data and metadata formats (Galgani, 2018) (see supplementary information for further details). A globally-agreed data management system enabling large-scale assessments could be supported by the Integrated Marine Debris Observing System (IMDOS, 2025) which, as envisioned by Maximenko et al., 2019, would also include modelling support to assess litter pathways and trends at large scales. A close collaboration

between data stewards and international imagery expertise is needed to develop widely agreed guidelines and to provide training on the use of new data management systems, for which experiences at large scale, such as EU coastline macrolitter (MSFD TG ML, 2025) and Regional Sea Conventions can serve as references [Box 3]. Quantitative data should then be accessible for different uses, including for the UN Global Platform on Plastic Pollution and Marine Litter (UNEP, 2025).

Limitations of imagery data management procedures may relate to (i) difficulties in agreeing on harmonised units when quantifying litter observations, either in absolute terms or relative to the area size; (ii) lack of quality assurance procedures in the data acquisition and description, such as inter-/intra-observer agreement; and (iii) the sheer volume of image data that researchers are no longer able to process by themselves.

It is proposed to annotate and archive the original data so that the extracted quantitative data and the original visual data are FAIR. Additional information, even if not part of the mandatory data, can also be very valuable to improve data interpretation. The associated meta-data should meet the highest scientific standards, such as the recently proposed FAIR Digital Objects for images (iFDOs) (Schoening et al., 2022) or INSPIRE rules. Image and video data should preferably be annotated with at least bounding boxes as prerequisites for the successful training and development of AI methods to screen visual data for marine litter.

Regional initiatives (e.g., EMODNET, NOAA) and global platforms (e.g., G20 (Intergovernmental forum comprising 19 sovereign countries, the European Union and the African Union) Ministry of Environment Japan, GOOS) support marine litter monitoring and occasionally include seafloor litter data. Early large-scale studies conducted from the 1990s and in the 2000s (e.g. Galgani et al., 1995, Gulf of Lion; Stefatos et al., 1999, Patras Gulf), relying mostly on trawling, led to later publications (e.g., Ioakeimidis et al., 2014; Galgani et al., 2022). This, together with limited imagery-based monitoring, has highlighted decades old litter pollution, including in remote areas.

Text Box 3

Legacy data

Legacy data on seafloor litter could be valuable for assessing trends, setting baselines, or informing site selection. However, users should be aware of their limitations, particularly biases in trawling data, such as missing items, or count issues due to fragmentation. Legacy imagery offers some advantages over trawling but also some disadvantages (Canals et al., 2021). A common problem with legacy trawls and images often refers to location uncertainty and poor associated metadata, along with a wide disparity in the classification of litter items. In any case, legacy data are worth being checked for their potential use, in particular for areas with little or no monitoring coverage. They should be subject to a quality check or at least an uncertainty estimate for relevant parameters before being integrated into assessments.

4. Link with mitigation measures

While ongoing monitoring schemes of marine litter, such as coastal surveys, provide valuable information on common types of litter, some important types of litter require additional seafloor assessments. These include fisheries-related litter, high-density plastics, and other types of litter from both land-based and sea-based sources. Seafloor assessments are also essential to identify areas where litter accumulates. Large-scale assessments are needed to evaluate the effectiveness of mitigation strategies and could guide environmentally safe plastic removal efforts (Bergmann et al., 2023) wherever feasible in accessible accumulation areas.

5. Recommendations

- Site selection and strategy for new surveys should respond to critical questions and goals, such as e.g. trend assessments and hotspot identification.
- Acquire robust and extensive data on litter distribution, abundance, types and size ranges across marine habitats as this is of utmost importance for informed actions.
- Acquire seafloor macrolitter data through widely agreed, harmonised, and non-destructive methods, providing training and capacity building on their use, and encompassing advanced technologies, including the use of new and legacy imagery.
- Use, to the best possible extent, surveys for environmental, industrial and exploration purposes for seafloor litter monitoring, including from already existing imagery.
- Establish agreed data formats, units and metadata, as they are critical to enable global management of data.
- Ensure the confluence of data into a global baseline assessment, making best use of regional developments.
- Provide litter assessments to inform policy-making and identify the need for action through upstream measures or targeted actions, including litter removal activities in accumulation areas where this can be done in an environmentally safe, efficient and appropriate manner, in accordance with science-based criteria.

Following all of the above recommendations will help placing seafloor macrolitter (and megalitter) as a vital part of the evidence to inform global mitigation measures.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.marpolbul.2025.118500>.

Data availability

No data was used for the research described in the article.

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