Marine Pollution Bulletin 221 (2025) 118500

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

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

Georg Hanke [a,*], Miquel Canals [b,c,d], Ryota Nakajima [e], Melanie Bergmann [f], Francois Galgani [g], Daoji Li [h], George Papatheodorou [i], Christopher Kim Pham [j], Diva J. Amon [k,l], Michela Angiolillo [m,n], Lene Buhl-Mortensen [o], Alessandro Cau [p], Pierpaolo Consoli [q], Jaime Selina Davies [r,s], Carlos Dominguez-Carrió [t,u], Carlos M. Duarte [v], Alessandra Giorgetti [w], Bjørn Einar Grøsvik [o], Lars Gutow [f], Veerle A.I. Huvenne [x], Christos Ioakeimidis [y], Viktor Komorin [z], Guangpeng Liu [aa], Lonny Lundsten [ab], Iryna Makarenko [ac], Anastasiia Martynova [v], Maria Eugenia Molina Jack [w], Tim W. Nattkemper [ad], Artur P. Palacz [ae], Marco Palma [af], Martina Pierdomenico [ag], Maria Pogojeva [ah], Marta Ruiz [ai], Luis F. Ruiz-Orejón [a], Josie Russell [aj], Xiujuan Shan [ak], Matias Valdenegro-Toro [al], Matteo Vinci [w], Nian Wei [am], Lucy C. Woodall [an], Shoufeng Zhang [ao]

[a] *Joint Research Centre, European Commission, Via E. Fermi, 2749, 21027 Ispra, VA, Italy*
[b] *Sustainable Blue Economy Chair, and CRG Marine Geosciences, Department of Earth and Ocean Dynamics, Faculty of Earth Sciences, University of Barcelona, Martí i Franquès, s/n, 08028 Barcelona, Spain*
[c] *Reial Academia de Ciencies i Arts de Barcelona (RACAB), La Rambla, 115, 08002 Barcelona, Spain*
[d] *Institut d'Estudis Catalans (IEC), Seccio de Ciencies i Tecnologia, Carrer del Carme, 47, 08001 Barcelona, Spain*
[e] *Japan Agency for Marine-Earth Science and Technology, 2-15 Natsushima-cho, Yokosuka, Kanagawa 237-0061, Japan*
[f] *Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI), Am Handelshafen 12, 27570 Bremerhaven, Germany*
[g] *IFREMER, 155 rue Jean-Jacques Rousseau, 92138 Issy-les-Moulineaux, France*
[h] *SKLEC, East China Normal University, 500 Dongchuan Road, Shanghai 200241, China*
[i] *University Patras, Oceanus-Lab, Department of Geology, University Campus, 26504 Patras, Greece*
[j] *Instituto de Investigação em Ciências do Mar – OKEANOS, Universidade dos Açores, Horta, Portugal*
[k] *Marine Science Institute, University of California Santa Barbara, Bldg. 520, Santa Barbara, California 93106-6150, USA*
[l] *SpeSeas, 38 Papillon Drive, Signature Park, D'abadie, WI, Trinidad and Tobago*
[m] *Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), Via Vitaliano Brancati 48, 00144 Rome, Italy*
[n] *Stazione Zoologica Anton Dohrn (SZN), Villa Comunale, 80121 Naples, Italy*
[o] *Institute of Marine Research, Postboks 1870, Nordnes, 5817 Bergen, Norway*
[p] *Department of Life and Environmental Sciences, University of Cagliari, Via T. Fiorelli 1, 09126 Cagliari, Italy*
[q] *Stazione Zoologica Anton Dohrn, Sicily Marine Centre, Department of Integrative Marine Ecology (EMI), Villa Pace - Contrada Porticatello 29, 98167 Messina, Italy*
[r] *Plymouth University: Drake Circus, Plymouth PL4 8AA, UK*
[s] *University of Gibraltar: Europa Point, Gibraltar*
[t] *Instituto de Investigação em Ciências do Mar – OKEANOS, Universidade dos Açores, 862 Horta, Portugal*
[u] *Institut de Ciències del Mar (ICM-CSIC), Passeig Marítim de la Barceloneta 37-49, 08003 Barcelona, Spain*
[v] *King Abdullah University of Science and Technology, 4700 King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia*
[w] *Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), Borgo Grotta Gigante 42/c, 34010 Sgonico, Italy*
[x] *National Oceanography Centre, European Way, Southampton SO14 3ZH, UK*
[y] *United Nations Environment Programme / Coordinating Unit for the Mediterranean Action Plan - Barcelona Convention Secretariat, 48, Vassileos Konstantinou Ave., 116 35 Athens, Greece*
[z] *Ukrainian scientific center of Ecology of Sea (UkrSCES), 89 Frantsuzsky Blvd., 65009 Odesa, Ukraine*
[aa] *State Key Lab. of Estuarine and Coastal Research, East China Normal University, 3663 North Zhongshan Road, Shanghai 200062, China*
[ab] *Monterey Bay Aquarium Research Institute (MBARI), Monterey, 7700 Sandholdt Road, Moss Landing, CA 95039, USA*
[ac] *Black Sea Commission, Maslak Mahallesi, Büyükdere Caddesi, No 265, 34398 Sarıyer, Istanbul, Türkiye*
[ad] *Biodata Mining Group, Faculty of Technology, Bielefeld University, Universitätsstraße 25, 33615 Bielefeld, Germany*
[ae] *Institute of Oceanology Polish Academy of Sciences, Sopot, Powstancow Warszawy 55, 81-712 Sopot, Poland*
[af] *UniSystems Luxemburg S.a.r.l. (work carried out at JRC), ATRIUM Business Park - Rue Du Puits Romain, 29 BERTRANGE L, 8070 Luxembourg, Luxembourg*
[ag] *Istituto Di Geologia Ambientale E Geoingegneria – Consiglio Nazionale delle Ricerche (IGAG-CNR), Via B. Castiglione 2, 00142 Rome, Italy*

* Corresponding author.
E-mail address: georg.hanke@ec.europa.eu (G. Hanke).

https://doi.org/10.1016/j.marpolbul.2025.118500
Received 12 May 2025; Received in revised form 21 July 2025; Accepted 23 July 2025
Available online 9 August 2025

[ah] UNDP Istanbul Regional Hub and CIS, Merkez, Abide-i Hürriyet Cd No:142, 34381 Şişli, İstanbul, Turkey
[ai] HELCOM - Baltic Marine Environment Protection Commission, Katajanokanlaituri 6B, 00160 Helsinki, Finland
[aj] Centre for Environment, Fisheries and Aquaculture Science (Cefas), Pakefield Road, Lowestoft NR33 0HT, UK
[ak] Yellow Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences, 106 Nanjing Road, Qingdao 266071, China
[al] University of Groningen, Nijenborgh 9, 9747 AG Groningen, Netherlands
[am] East China Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences, 300 Jungong Road, Shanghai 200090, China
[an] Centre for Ecology and Conservation, University of Exeter, Penryn, Cornwall TR10 9FE, UK
[ao] National Marine Environmental Monitoring Center, 42, Linghe Street, Dalian 116023, China

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 herarchical 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.

Exisiting 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; Sciutteri 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-Carrió 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-Carrió 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 metadata 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.

References

Amon, D.J., Kennedy, B.R.C., Cantwell, K., Suhre, K., Glickson, D., Shank, T.M., Rotjan, R.D., 2020. Deep-sea debris in the Central and Western Pacific Ocean. Front. Mar. Sci. 7 (369). https://doi.org/10.3389/fmars.2020.00369.

Anastasopoulou, A., Fortibuoni, T., 2019. Impact of plastic pollution on marine life in the Mediterranean Sea. In: Stock, F., et al. (Eds.), Plastics in the Aquatic Environment - Part I. The Handbook of Environmental Chemistry, vol 111. Springer, Cham, pp. 135–196. https://doi.org/10.1007/698_2019_421.

Angiolillo, M., Fortibuoni, T., 2020. Impacts of marine litter on Mediterranean reef systems: from shallow to deep waters. Front. Mar. Sci. 7, 581966. https://doi.org/10.3389/fmars.2020.581966.

Angiolillo, M., et al., 2021. Distribution of seafloor litter and its interaction with benthic organisms in deep waters of the Ligurian Sea (Northwestern Mediterranean). Sci. Total Environ. 788, 147745. https://doi.org/10.1016/j.scitotenv.2021.147745.

Angiolillo, M., et al., 2022. A *Dendrophyllia ramea* population in the Ionian Sea (Central Mediterranean Sea) threatened by anthropogenic impacts. Front. Mar. Sci. 9, 838274. https://doi.org/10.3389/fmars.2022.838274.

Barry, P.J., et al., 2024. Seafloor macrolitter as a settling platform for non-native species: a case study from UK waters. Mar. Pollut. Bull. 204, 116499. https://doi.org/10.1016/j.marpolbul.2024.116499.

Battaglia, P., et al., 2019. Colonization of floats from submerged derelict fishing gears by four protected species of deep-sea corals and barnacles in the Strait of Messina (central Mediterranean Sea). Mar. Pollut. Bull. 148, 61–65. https://doi.org/10.1016/j.marpolbul.2019.07.073.

Belcher, B.T., et al., 2023. Demystifying image-based machine learning: a practical guide to automated analysis of field imagery using modern machine learning tools. Front. Mar. Sci. 10, 1157370. https://doi.org/10.3389/fmars.2023.1157370.

Bell, K.L.C., et al., 2022. Low-cost, deep-sea imaging and analysis tools for deep-sea exploration: a collaborative design study. Front. Mar. Sci. 9, 873700. https://doi.org/10.3389/fmars.2022.873700.

Bell, K.L.C., Quinzin, M.C., Amon, D., Poulton, S., Hope, A., Sarti, O., Cañete, T.E., Smith, A.M., Baldwin, H.I., Lira, D.M., Cambronero-Solano, S., Chung, T.-R.A., Brady, B., 2023. Exposing inequities in deep-sea exploration and research: results of the 2022 global deep-sea capacity assessment. Front. Mar. Sci. 10, 1217227. https://doi.org/10.3389/fmars.2023.1217227.

Bell, K.L.C., Johannes, K.N., Kennedy, B.R.C., Poulton, S.E., 2025. How little we've seen: a visual coverage estimate of the deep seafloor. Sci. Adv. 11, eadp8602.

Benoist, N.M.A., et al., 2019. Monitoring mosaic biotopes in a marine conservation zone by autonomous underwater vehicle. Conserv. Biol. 33 (5), 1174–1186. https://doi.org/10.1111/cobi.13312.

Bergmann, et al., 2023. Moving from symptom management to upstream plastics prevention: the fallacy of plastic cleanup technology. One Earth 2023. https://doi.org/10.1016/j.oneear.2023.10.022.

Bruemmer, A.L., et al., 2023. Marine litter-fauna interactions: a standardised reporting framework and critical review of the current state of research with a focus on submarine canyons. Front. Mar. Sci. 10, 1225114. https://doi.org/10.3389/fmars.2023.1225114.

Buhl-Mortensen, L., Buhl-Mortensen, P., 2017. Marine litter in the Nordic Seas: distribution composition and abundance. Mar. Pollut. Bull. 125 (1–2), 260–270. https://doi.org/10.1016/j.marpolbul.2017.08.048.

Canals, M., et al., 2021. The quest for seafloor macrolitter: a critical review of background knowledge, current methods and future prospects. Env. Res. Lett. 16, 023001. https://doi.org/10.1088/1748-9326/abc6d4.

Carugati, L., et al., 2021. Colonization of plastic debris by the long-lived precious red coral *Corallium rubrum*: new insights on the "plastic benefits" paradox. Mar. Poll. Bull. 165, 112104. https://doi.org/10.1016/j.marpolbul.2021.112104.

Consoli, et al., 2024. Synthetic polymers: a global threat to aquatic benthic environments. J. Hazard. Mater. 474, 134848. https://doi.org/10.1016/j.jhazmat.2024.134848.

Consoli, P., Scotti, G., Romeo, T., Fossi, M.C., Esposito, V., D'Alessandro, M., Battaglia, P., Galgani, F., Figurella, F., Pragnell-Raasch, H., Andaloro, F., 2020. Characterization of seafloor litter on Mediterranean shallow coastal waters: evidence from Dive Against Debris®, a citizen science monitoring approach. Mar. Pollut. Bull. 150, 110763. https://doi.org/10.1016/j.marpolbul.2019.110763.

de Carvalho-Souza, G.F., et al., 2018. Marine litter disrupts ecological processes in reef systems. Mar. Pollut. Bull. 133, 464–471. https://doi.org/10.1016/j.marpolbul.2018.05.049.

Dominguez-Carrió, C., et al., 2020. Seafloor litter sorting in different domains of Cap de Creus continental shelf and submarine canyon (NW Mediterranean Sea). Mar. Pollut. Bull. 161, 111744. https://doi.org/10.1016/j.marpolbul.2020.111744.

Dominguez-Carrió, C., et al., 2021. A cost-effective video system for a rapid appraisal of deep-sea benthic habitats: The Azor drift-cam. Methods Ecol. Evol. 12 (8), 1379–1388. https://doi.org/10.1111/2041-210X.13617.

Duncan, E.M., et al., 2023. Predicting the distribution and abundance of abandoned, lost or discarded fishing gear (ALDFG) in the deep sea of the Azores (North Atlantic). Sci. Total Environ. 900, 166579. https://doi.org/10.1016/j.scitotenv.2023.166579.

Fleet, D., et al., 2021. A joint list of litter categories for marine macrolitter monitoring. In: EUR 30348 EN. Publ. Office of the European Union, Luxembourg. https://doi.org/10.2760/127473. JRC121708.

Galgani, F., 2018. Guidelines and forms for gathering marine litter data. In: EMODnet Thematic Lot n° 4—Chemistry, p. 58.

Galgani, F., et al., 1995. Distribution and abundance of debris on the continental shelf of the north-western Mediterranean Sea. Mar. Pollut. Bull. 30 (11), 713–717.

Galgani, F., et al., 2013. Marine litter within the European Marine Strategy Framework Directive. ICES J. Mar. Sci. 70, 1055–1064. https://doi.org/10.1093/icesjms/fst122.

Galgani, F., et al., 2022. Marine litter, plastic, and microplastics on the seafloor. In: Andrady, A.L. (Ed.), Plastics and the Ocean: Origin, Characterization, Fate, and Impacts. John Wiley & Sons, Inc., pp. 151–187. https://doi.org/10.1002/9781119768432.ch6

Gall, S.C., Thompson, R.C., 2015. The impact of debris on marine life. Mar. Pollut. Bull. 92, 170–179. https://doi.org/10.1016/j.marpolbul.2014.12.041.

GESAMP, 2019. Guidelines on the monitoring and assessment of plastic litter and microplastics in the ocean. In: Kershaw, P.J., Turra, A., Galgani, F. (Eds.), (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP/ISA Joint Group of

Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP No. 99, 130p.
Gomes-Pereira, J.N., et al., 2016. Current and future trends in marine image annotation software. Prog. Oceanogr. 149, 106–120. https://doi.org/10.1016/j.pocean.2016.07.005.
Hanke, G., et al., 2025. Marine litter in the deepest site of the Mediterranean Sea. Mar. Pollut. Bull. 213, 117610. https://doi.org/10.1016/j.marpolbul.2025.117610.
IMDOS, 2025. Website of IMDOS, the Integrated Marine Debris Observing System. https://imdos.org/. Accessed in July 2025.
Ioakeimidis, C., Zeri, C., Kaberi, H., Galatchi, M., Antoniadis, K., Streftaris, N., Galgani, F., Papathanassiou, E., Papatheodorou, G., 2014. A comparative study of marine litter on the seafloor of coastal areas in the Eastern Mediterranean and Black Seas. Mar. Pollut. Bull. 89, 296–304. https://doi.org/10.1016/j.marpolbul.2014.09.044.
Japanese Ministry of Environment, 2025. Website of the AOMI Atlas of Ocean Microplastic. https://aomi.env.go.jp/. Acessed in July 2025.
Jenkins, T., et al., 2022. Current state of microplastic pollution research data: trends in availability and sources of open data. Front. Environ. Sci. 10, 912107. https://doi.org/10.3389/fenvs.2022.912107.
Katija, K., et al., 2022. Fathomnet: a global image database for enabling artificial intelligence in the ocean. Sci. Rep. 12, 15914. https://doi.org/10.1038/s41: 598-022-19939-2.
Kouvara, K., et al., 2025. Assessing marine litter and its ecological impact on the seafloor of Thermaikos Gulf (NE Mediterranean Sea, Greece): insights from ROV and diver surveys. Mar. Pollut. Bull. 217, 118109. https://doi.org/10.1016/j.marpolbul.2025.118109.
Kühn, S., et al., 2015. Deleterious effects of litter on marine life. In: Bergmann, M., et al. (Eds.), Marine Anthropogenic Litter. Springer, Cham, Switzerland, pp. 75–116. https://doi.org/10.1007/978-3-319-16510-3_4.
Langenkämper, D., et al., 2017. BIIGLE 2.0—browsing and annotating large marine image collections. Front. Mar. Sci. 4, 83. https://doi.org/10.3389/fmars.2017.00083.
Ma, D., et al., 2023. MLDet: Towards efficient and accurate deep learning method for marine litter detection. Ocean Coast. Manag. 243, 106765. https://doi.org/10.1016/j.ocecoaman.2023.106765.
Marcon, Y., Purser, A., 2017. PAPARA(ZZ) I: an open-source software interface for annotating photographs of the deep-sea. SoftwareX 6, 69–80. https://doi.org/10.1016/j.softx..2017.02.002.
Martynova, A., Rodrigue, M., Pieribone, V., Qurban, M., Duarte, C.M., 2024. Density and distribution patterns of seafloor macrolitter in the eastern Red Sea. Sci. Total Environ. 953, 176042. https://doi.org/10.1016/j.scitotenv.2024.176042.
Matabos, M., Cottais, P., Leroux, R., Cenatiempo, Y., Gasne-Destaville, C., Roullet, N., Sarrazin, J., Tourolle, J., Boremans, C., 2025. Deep sea spy: an online citizen science annotation platform for science and ocean literacy. Ecol. Inform. 86, 103065. https://doi.org/10.1016/j.ecoinf.2025.103065.
Maximenko, N., et al., 2019. Toward the integrated marine debris observing system. Front. Mar. Sci. 6, 447. https://doi.org/10.3389/fmars.2019.00447.
Molina Jack, M.E., et al., 2019. EMODnet marine litter data management at pan-European scale. Ocean Coast. Manag. 181, 104930. https://doi.org/10.1016/j.ocecoaman.2019.104930.
Mordecai, G., et al., 2011. Litter in submarine canyons off the west coast of Portugal. Deep-Sea Res. II 58, 2489–2496. https://doi.org/10.1016/j.dsr2.2011.08.009.
MSFD TG ML, Marine Strategy Framework Directive, Technical Group on Marine Litter, 2023. Guidance on the Monitoring of Marine Litter in European Seas An update to improve the harmonised monitoring of marine litter under the Marine Strategy Framework Directive. In: EUR 31539 EN, 2023. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/59137. ISBN 978-92- 68-04093-5. JRC133594.
MSFD TG ML, Marine Strategy Framework Directive Technical Group on Marine Litter, 2025. European Coastline Macro Litter Trends 2015–2021, 2025. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/0752301, JRC138907.
Nakajima, R., et al., 2014. A new method for estimating the area of the seafloor from oblique images taken by deep-sea submersible survey platforms. JAMSTEC Rep. Res. Dev. 19, 59–66. https://doi.org/10.5918/jamstecr.19.59.
Novy, D., et al., 2022. Maka Niu: a low-cost, modular imaging and sensor platform to increase observation capabilities of the deep ocean. Front. Mar. Sci. 9, 986237. https://doi.org/10.3389/fmars.2022.986237.
Ontrup, J., 2009. BIIGLEWeb 2.0 enabled labelling and exploring of images from the Arctic deep-sea observatory HAUSGARTEN. OCEANS 2009-Europe (Bremen, Germany), pp. 1–7.
Parga Martínez, K.B., et al., 2020. Temporal trends in marine litter at three stations of the HAUSGARTEN observatory in the Arctic deep sea. Front. Mar. Sci. 5, 321. https://doi.org/10.3389/fmars.2020.00321.
Pham, C.K., et al., 2013. Abundance of litter on Condor Seamount (Azores, Portugal, Northeast Atlantic). Deep-Sea Res. II 98, 204–208. https://doi.org/10.1016/j.dsr2.2013.01.011.
Picheral, M., et al., 2017. EcoTaxa, a tool for the taxonomic classification of Images. available at http://ecotaxa.obs-vlfr.fr.
Pierdomenico, M., et al., 2019. Massive benthic litter funnelled to deep sea by flash-flood generated hyperpycnal flows. Sci. Rep. 9, 5330. https://doi.org/10.1038/s41598-019-41816-8.
Purser, A., Hoge, U., Lemburg, J., Bodur, Y., Schiller, E., Ludszuweit, J., Greinert, J., Dreutter, S., Dorschel, B., Wenzhöfer, F., 2020. PlasPI marine cameras: open-source, affordable camera systems for time series marine studies. HardwareX 7, e00102. https://doi.org/10.1016/j.ohx.2020.e00102.
Rodríguez, Y., Pham, C.K., 2017. Marine litter on the seafloor of the Faial-Pico Passage, Azores Archipelago. Mar. Pollut. Bull. 116 (1–2), 448–453. https://doi.org/10.1016/j.marpolbul.2017.01.018.
Sandra, M., et al., 2023. A systematic review of state-of-the-art technologies for monitoring plastic seafloor litter. J. Ocean Eng. Sci. https://doi.org/10.1016/j.joes.2023.07.004.
Santin, A., et al., 2020. First report of the carnivorous sponge *lycopodina hypogea* (Cladorhizidae) associated with marine debris, and its possible implications on deep-sea connectivity. Mar. Pollut. Bull. 159, 1–7. https://doi.org/10.1016/j.marpolbul.2020.111501.
Schlining, B.M., Jacobsen Stout, N., 2006. MBARI's video annotation and reference system. OCEANS 2006, Boston, MA, USA, pp. 1–5.
Schlining, K., et al., 2013. Debris in the deep: using a 22-year video annotation database to survey marine litter in Monterey Canyon, central California, USA. Deep-Sea Res. I 79, 96–105. https://doi.org/10.1016/j.dsr.2013.05.006.
Schoening, T., et al., 2016. RecoMIA—recommendations for marine image annotation: lessons learned and future directions. Front. Mar. Sci. 3, 59. https://doi.org/10.1016/j.mio.2016.04.002.
Schoening, T., et al., 2022. Making marine image data FAIR. Sci Data 9, 414. https://doi.org/10.1038/s41597-022-01491-3.
Sciutteri, V., Costa, V., Malara, D., Figurella, F., Campbell, I., Deery, E., Romeo, T., Andaloro, F., Consoli, P., 2024. Citizen science through a recreational underwater diving project supports the collection of large-scale marine litter data: the Oceania case study. Mar. Pollut. Bull. 200, 116133. https://doi.org/10.1016/j.marpolbul.2024.116133.
Song, X., et al., 2021. Large plastic debris dumps: new biodiversity hot spots emerging on the deep-sea floor. Environ. Sci. Technol. Lett. 8 (2), 148–154. https://doi.org/10.1021/acs.estlett.0c00967.
Stefatos, A., Charalampakis, M., Papatheodorou, G., Ferentinos, G., 1999. Marine debris on the seafloor of the Mediterranean Sea: examples from two enclosed gulfs in western Greece. Mar. Pollut. Bull. 38, 389–393. https://doi.org/10.1016/S0025-326X(98)00141-6.
Tekman, M.B., Gutow, L., Bergmann, M., 2022. Marine debris floating in arctic and temperate Northeast Atlantic waters. Front. Mar. Sci. 9. https://www.frontiersin.org/articles/10.3389/fmars.2022.933768.
Thompson, R.C., et al., 2004. Lost at sea: where is all the plastic? Science 304, 838. https://doi.org/10.1126/science.1094559.
Thurber, A.R., Sweetman, A.K., Narayanaswamy, B.E., Jones, D.O.B., Ingels, J., Hansman, R.L., 2014. Ecosystem function and services provided by the deep sea. Biogeosciences 11 (14), 3941–3963. https://doi.org/10.5194/bg-11-3941-2014.
Townsend Harris, P., Maes, T., Raubenheimer, K., Walsh, J.P., 2023. A marine plastic cloud - Global mass balance assessment of oceanic plastic pollution. Cont. Shelf Res. 255, 104947. https://doi.org/10.1016/j.csr.2023.104947.
UNEA, 2022. United Nations Environmental Assembly: End plastic pollution: towards an international legally binding instrument, UNEP/EA.5/Res.14. https://wedocs.unep.org/xmlui/bitstream/handle/20.500.11822/39764/END%20PLASTIC%20POLLUTION%20-%20TOWARDS%20AN%20INTERNATIONAL%20LEGALLY%20BINDING%20INSTRUMENT%20-%20English.pdf?sequence=1&isAllowed=y.
UNEP, 2022. United Nations Environmental Programme Website of the Intergovernmental Negotiating Committee on Plastic Pollution. https://www.unep.org/inc-plastic-pollution. Accessed in July 2025.
UNEP, 2025. Website of the United Nations Environment Programme Global Plastics Hub. https://globalplasticshub.org/. Accessed in July 2025.
UNESCO, 2025. Website of UNESCO's Ocean Decade. https://oceandecade.org/. Accessed in July 2025.
United Nations, 2025. Website of Sustainable Development Goal 14, Conserve and sustainably use the oceans, seas and marine resources for sustainable development. https://sdgs.un.org/goals/goal14. Accessed in July 2025.
Woodall, L.C., et al., 2014. The deep sea is a major sink for microplastic debris. R. Soc. Open Sci. 1, 140317. https://doi.org/10.1098/rsos.140317.
Zhao, F., Huang, B., Wang, J., Shao, X., Wu, Q., Xi, D., Liu, Y., Chen, Y., Zhang, G., Ren, Z., Chen, J., Mizuno, K., 2025. Seafloor debris detection using underwater images and deep learning-driven image restoration: a case study from Koh Tao, Thailand. Mar. Pollut. Bull. 214, 117710.
Zhu, X., Rochman, C.M., Hardesty, B.D., Wilcox, C., 2024. Plastics in the deep sea: A global estimate of the ocean floor reservoir. Deep-Sea Res. I Oceanogr. Res. Pap. 206, 104266. https://doi.org/10.1016/j.dsr.2024.104266.
Zurowietz, M., et al., 2019. BIIGLE2Go–a scalable image annotation system for easy deployment on cruises. In: Proc. of IEEE OCEANS 2019. Marseille, France.