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Revisiting the strategy for marine litter monitoring within the european marine strategy framework directive (MSFD)

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A B S T R A C T

Marine litter and non-degradable plastic pollution is of global concern. Regular monitoring programs are being established to assess and understand the scale of this pollution. In Europe, the goal of the European Marine Strategy Framework Directive (MSFD) is to assess trends in Good Environmental Status and support large-scale actions at the regional level. Marine litter monitoring requires tailored sampling strategies, protocols and indicators, that align with specific objectives and are tailored for local or regional needs. In addition, the uneven spatial and temporal distributions of marine litter present a challenge when designing a statistically powerful monitoring program. In this paper, we critically review the existing marine litter monitoring programs in Europe. We discuss the main constraints, including environmental, logistical, scientific, and ethical factors. Additionally, we outline the critical gaps and shortcomings in monitoring MSFD beaches/shorelines, floating litter, seafloor litter, microplastics, and harm. Several priorities must be established to shape the future of monitoring within the MSFD. Recent developments in analytical approaches, including optimizing protocols and sampling strategies, gaining a better understanding of the spatiotemporal heterogeneity of litter and its implications for survey design and replication, and the inclusion of newly validated methodologies that have achieved sufficient technical readiness, must be considered. Although there are well-established methods for assessing beaches, floating and seafloor litter, it will be necessary to implement monitoring schemes for microplastics in sediments and invertebrates as robust analytical methods become available for targeting smaller particle size classes. Furthermore, the inclusion of indicators for entanglement and injury to marine organisms will have to be considered in the near future. Moreover, the following actions will enhance the effectiveness of monitoring efforts: (1) creating an inventory of accumulation areas and sources of specific types of litter (e.g., fishing gear), (2) monitoring riverine inputs of litter, (3) monitoring atmospheric inputs including microplastics, (4) accidental inputs during extreme weather events, and (5) studying how species at risk may be transported by litter. We provide recommendations to support long-term, effective, and well-coordinated marine litter monitoring within the MSFD to achieve a comprehensive and accurate understanding of marine litter in EU waters. This will allow the development of measures to mitigate the impacts of marine pollution and eventually to evaluate the success of the respective measures.

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1. Introduction

The interest in anthropogenic litter and plastic pollution in the environment, driven by environmental, legal, and regulatory factors, has increased considerably over the last decade. Marine litter is a high-profile issue, reaching the public and raising awareness worldwide (González-Fernández and Hanke, 2022). The concern about plastic and microplastic pollution, along with the attention received from administrations and research funding schemes, is rapidly expanding. Litter and plastic pollution need complex solutions and now encompass all environmental compartments after originally focusing on marine environments only. For example, microplastics have recently been reported from atmospheric deposition samples in many regions worldwide, including remote polar regions (e.g., Dris et al., 2016; Allen et al., 2022; AMAP, 2021).

The established monitoring programmes for litter in marine systems contribute to the evidence base for most policy initiatives; they are thereby among the central scientific drivers behind societal actions on plastic pollution (Nielsen et al., 2023). The monitoring of marine litter started with small-scale activities, describing methodologies for the assessment of floating litter, and more extensive beach litter surveys, the latter being the most suitable method for large-scale data collection (GESAMP 2019). The first large-scale marine litter monitoring programmes refer to changes in the stomach contents of fulmars monitored since the 1980s in the Netherlands (Van Franeker and Meijboom, 2002; Van Franeker et al., 2021). The success of the programme led to its integration as a common indicator within the regional OSPAR Commission for the North–East Atlantic region (Kühn et al., 2022). Furthermore, regular beach litter monitoring along the coast within the OSPAR region has been performed since 2001 (Schultze et al., 2017).

Gradually, several national and international institutions began planning or have already implemented regular monitoring programmes that investigate not only beaches but also floating litter (in the water surface layer), litter found on the seafloor, and litter inside marine biota in their marine litter assessments (Galgani et al., 2000; Van Franeker and Meijboom, 2002; Ryan et al., 2009; Ryan, 2015; Van Franeker et al., 2021). In Europe, the Marine Strategy Framework Directive (MSFD) and the four Regional Sea Conventions (RSCs), OSPAR Commission for the Northeast Atlantic region, HELCOM (Helsinki Commission – Baltic Marine Environment Protection Commission), Black Sea Commission (BSC) and UNEP/MAP Barcelona Convention for the Mediterranean Sea are providing frameworks for monitoring and large-scale actions to assess and mitigate the impacts of marine litter. More recently, the MSFD (MSFD, 2008/56/EC) launched its regular monitoring of marine litter in the European region. Finally, the Arctic Council, which crosses over Nordic EU waters, initiated the AMAP (Arctic Monitoring and Assessment Programme) Litter and Microplastics Monitoring Plan in 2021, which includes monitoring and assessing litter and microplastic pollution to inform policy and decision-makers (AMAP, 2021).

The goals of monitoring programs include the assessment of trends toward Good Environmental Status (GES) and the identification of impacts of marine litter on marine ecosystems. The obtained monitoring data facilitate the selection of measures to reduce litter inputs and the evaluation of the effectiveness of such measures (GESAMP, 2019; Galgani et al., 2021). However, due to the status of analytical protocols and the relatively recent start of measuring plastics in marine environments, there are still significant data and knowledge gaps. The lack of agreed upon methodologies for collecting field data hinders the harmonization, coherence, and comparability of monitoring and assessment approaches (GESAMP, 2019). In addition, there is an increasing number of research initiatives in this field, leading to a diversification of methodologies that can both positively and negatively impact the development of monitoring approaches (Aliani et al., 2023). Given the changing environmental, societal, and policy perspectives, refining and optimizing monitoring strategies have become critical, as have potential changes in priorities and the need for more coordination.

Building on the work performed within the EU project EURO-qCHARM and exchanges with scientists from the EU MSFD Technical Group on Marine Litter (TGML) through a common workshop, we present a critical discussion of strategies and possible improvements to marine litter monitoring in Europe. It is not designed as a deep analysis of results but rather to review and analyze the marine litter monitoring approaches developed by the MSFD and suggest refinements to support efficient, coordinated, and harmonized monitoring, enabling more relevant assessments at the trans-national level.

2. Current monitoring of marine litters in europe

The Marine Strategy Framework Directive (MSFD, 2008/56/EC) is a comprehensive legislation to protect the marine environment across Europe and consists of a detailed implementation procedure. The marine litter field includes efforts directed toward its monitoring and toward implementing measures for its reduction in Europe. It is a policy framework for 22 coastal Member States (MS) of the European Union (EU) bordering four European Sea Basins, namely, the Mediterranean Sea, Black Sea, Baltic Sea, and Northeast Atlantic Ocean, encompassing 68,000 km of coastline. Within each MS, the implementation of the MSFD involved an initial assessment of the current environmental status and environmental impact (initiated in 2010–2012), the determination of Good Environmental Status (GES), the establishment of environmental targets and associated indicators, and the development of a monitoring program with cost estimates. Within the MSFD, the EU included marine litter as a descriptor (Descriptor 10, or D10) for a GES to be reached by 2020 (MSFD, 2008/56/EC), with targets to be updated during the next cycle (2024–2030).

Regular monitoring within the MSFD relies on common protocols, as presented in the original *Guidance on Monitoring of Marine Litter in European Seas* (Galgani et al., 2013) and its 2023 update (Galgani et al., 2023). This review describes general approaches and strategies for monitoring litter deposited on beaches, on the seafloor, at the sea surface and interactions with biota (ingestion and other interactions, such as entanglement), and on microplastics (in marine environments and biota). Criteria defined within the MSFD (COM DEC, 2017/848/EC, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32017D0848, revision in progress) include primary criteria established at the EU level and consider the composition, amount and spatial distribution of litter, excluding microlitter (<5 mm) for Descriptor 10 (Marine Litter) Criterion 1 (D10C1) and microlitter (<5 mm) for Descriptor 10 Criterion 2 (D10C2). The secondary criteria to be established through regional collaboration were the amount of litter and microlitter ingested by marine animals according to Descriptor 10 Criterion 3 (D10C3) and the number of individuals per species adversely affected by entanglement and other adverse effects according to Descriptor 10 Criterion 4 (D10C4).

The decision of the EU commission, COM DEC 2017/848/EC, provides definitions and frameworks for MS to establish threshold values for the assessment of GES through regional or subregional cooperation in the EU, which requires the availability of a well-established monitoring framework. The setup of monitoring approaches, collection of data for baseline analysis and development of thresholds are performed in collaboration among the EU MS and RSC within the EU-TGML (https://mcc.jrc.ec.europa.eu/main/dev.py?N=41&O=453 and https://mcc.jrc.ec.europa.eu/main/dev.py?N=41&O=454).

As is well defined by existing initiatives from RSC and EU MSFD, the purpose of monitoring is also to provide a framework to define baseline values in the EU region for pollution with litter and microplastics that will allow the identification of spatial and temporal trends in the coming years (Hanke et al., 2019). Data on the composition of litter from monitoring programmes provide additional information for assessing the effectiveness of marine litter mitigation measures from various marine litter action plans, either at the EU level (e.g., the Single Use Plastics Directive, EU, 2019/904) or through the RSC in EU regions.

Monitoring data will also provide information on the effects of litter and microplastics on biotic and abiotic compartments, supporting impact studies and risk assessments that may be performed in the future (Compa et al., 2019). Monitoring is implemented in all EU MS, albeit diversely, based on various initiatives across national, regional, EU, interregional or global scales (Table 1). Such diversity, however, often compromises the comparability of the obtained data (Lusher and Primpke, 2023), especially with regard to analyses of the smaller size classes of microplastics (Primpke et al., 2022). At the EU level, an analysis of EU projects on marine litter indicated that monitoring has been largely supported or coordinated by the EU through various initiatives (e.g., JPI Oceans) or Directorate Generals (DG ENV, DG Mare, DG RI, DG Regions, etc.). In 2019, monitoring represented 43% of the 52 funded projects in the EU (Maes et al., 2019).

Table 1
Ongoing EU international initiatives related to the monitoring of marine litter and/or microplastics (adapted and completed from UNEP, 2021).

DATA COLLECTION FRAMEWORKS and DATABASES												
NAME	DESCRIPTION	ACTIVITIES				INDICATORS						
		Coordination	Data aquisition	Compilation	Analysis	Beach/ shoreline	Surface water	Seafloor	Microplastics	Harm	Riverine inuts	Atmospheric inputs
Litterbase*	Marine litter references and maps, Worldwide			■		■	■	■	■	■	■	■
NOAA/ Tide*	Trash Information and data for Education & Solutions			■		■	■					
NOAA/ Marine tracker	Smartphone application for marine debrisr	■		■		■	■					
NOAA/ NCEI	Aggregated global data on microplastics	■		■		■			■			
MOEJ/ AOMI	Ministry of Environment, Japan	■	■	■	■				■			
GGGI*	Ghost Gear Initiative	■	■		■	■	■	■				
ODIMS*	OSPAR data repository			■		■		■		■		
ICES/DATRAS*	ICES database	■		■				■				
ICES/DOME*	ICES database	■		■					■	■		
MEDITS*	Mediterranean International Trawl Survey	■	■	■	■	■	■	■	■	■		
INFO RAC	UNEP MAP database*	■	■	■	■	■	■	■	■	■		
AWARE*	Dive Against Debris program (NGO)	■	■	■	■		■					
EMODnet	EU marine litter data repository	■	■	■		■	■	■	■			
Sea datanet	Pan EU infrastructure/ Marine data	■	■			■	■	■	■	■		

* Not only EU, ** Regional Sea Convention,

Legend

ACTIVITIES: Coordination; Compilation; Data; Analysis

INDICATORS: Beach / shoreline; Surface water; seafloor; Microplastics; harm; Riverine inputs; Atmospheric inputs

3. An analysis of monitoring constraints and strategies

Since monitoring is dependent on objectives (GESAMP, 2019), one must tailor the sampling strategies, protocols, and indicators to the specific questions being asked. As defined by Provencher et al. (2022), monitoring can include “baseline monitoring or initial assessments” to establish benchmark levels for a specific area at a specific point in time, “trend monitoring” to detect changes across temporal and/or spatial scales, and “source monitoring or surveillance monitoring” to monitor potential point sources/specific pressures. Additional monitoring methods may be considered, such as “compliance monitoring” to ensure that regulatory requirements/standards are met and “impact monitoring” to evaluate the effects of plastic pollution and related contaminants.

For marine litter, existing approaches and the establishment of monitoring strategies are inhibited by various constraints (UNEP/MAP SPA/RAC, 2018) that are methodological (e.g., relevant and referenced protocols are available, data collection schemes are in place, etc.), environmental (e.g., data are representative of the state of the environment, sources can be evaluated, etc.), biological (e.g., harm is understood, target species have a wide distribution to cover sufficient areas, etc.), logistical (e.g., accessibility, costs, etc.), and ethical (e.g., known protection status of the target species, destructive sampling is prohibited, etc.). Monitoring must also relate to established baselines and benchmark levels so that the results of subsequent surveys can be compared with the initial situation, and any changes, possibly in relation to reduction measures, can be evaluated when appropriate. Scientifically, however, baselines cannot be defined for some categories of litter (glass, metals) due to the limited number of items found at sea. Thus, sampling design (robustness of the approach, replicates, significance of changes, etc.) has been critical for decades to obtain sufficient statistical power for trend analyses and interpretation.

There are multiple aspects of survey design to consider when optimizing monitoring approaches, including the level of replication, the independence of sampling points, the frequency of sampling, and the plot/transect area/length, all of which impact the accuracy and precision of the monitoring scheme, its statistical relevance, and its ability to detect changes in space or time (Schulz et al., 2017). The spatial variation in litter density can be extremely high across different spatial scales in all compartments (Haarr et al., 2022; van Sebille et al., 2020). Consequently, regional, and local geographic variability need to be accounted for at different scales for representative monitoring if the objective is a holistic understanding of baselines and trends. Attempts have been made to quantify spatial autocorrelation and determine what constitutes independent samples (Goldstein et al., 2013; SALT 2022), but this remains poorly understood. Spatial (and temporal) autocorrelation results in pseudo-replication if not adequately accounted for in analyses, and the potential need for nesting during statistical analyses (i.e., mixed models) must be considered (e.g., for individual ROVs obtained from seafloor images along transects, beaches in relatively close proximity) (Haarr et al., 2022).

The methods and protocols in over 3000 published papers on monitoring nano, micro, and macroplastics in various compartments were recently analyzed (Aliani et al., 2023). Some of the main conclusions were that research studies on plastics are unevenly distributed, with insufficient method descriptions and differences in matrices used, and full datasets are not generally publicly available. There is also a high heterogeneity of methods and a very limited number of studies on small particles or specific compartments (e.g., sediment microplastics, Galgani et al., 2022). This stresses the need for the development and optimization of integrated and harmonized monitoring frameworks/protocols. As a result of the work by Aliani et al. (2023), several recommendations for monitoring were proposed to ensure that new data can be harmonized and used across a large scale. The work also identified six fundamental steps that form Reproducible Analytical Pipelines (RAP) for effective analysis in any plastic size and environmental matrix. Finally, a scale of technological readiness was provided to support a more efficient and cost-effective approach to guideline development.

4. Gaps related to ongoing monitoring within MSFD

Within MSFD, there are areas where improvements can be made to enhance the comprehensiveness and accuracy of monitoring. The need for expanded coverage, improved site selection strategies, inclusion of new indicators or approaches, and the identification of challenges and potential solutions for each of the criteria are critical steps before further improvements. Addressing these gaps and advancing our understanding of the environmental drivers of debris accumulation will enable better implementation of cost-effective abatement measures and the attainment of good environmental status (GES).

Monitoring is now in place in most European Sea areas for beaches and shoreline litter (>2.5 cm in size). It is based on an updated list of items and has baseline and threshold values, allowing the definition of GES and the setting of operational, environmental, or political objectives (Van Loon et al., 2020). The recent regional trend and status assessments performed within the HELCOM and OSPAR frameworks (Lacroix et al., 2022; HELCOM, 2023), provided recommendations and data requirements (Walvoort and van Loon, 2022). Aggregating data from different monitoring sites at the (sub)regional or national scales, needs a minimum of 40 surveys from sites with a minimum of 5 years and 10 surveys evenly distributed in time. Currently, such an approach is also considered for EU-wide assessments within TGML.

Typically, beach litter monitoring is regarded as suitable for participatory science (GESAMP, 2019), but there are limitations to this approach. Participatory monitoring should be based on simple approaches (e.g., smartphone apps) that participants can easily use. Furthermore, solid training should be included within the constraints of the MSFD. Additionally, the MSFD has not considered mesoplastics (5 mm-2.5 cm) or microplastics to date, which are important for addressing the complete coverage of beach litter pollution. An MFSD protocol for monitoring mesolitter and pellets on beaches has been developed and is currently in a phase for test implementation (Galgani et al., 2023).

For floating macrolitter, assessments within the MSFD are poorly developed. MS have identified several limitations, including the subjective implementation of observation protocols, challenges related to rough seas and visibility, and the need for large-scale sweeping to ensure consistent results. The existing observation protocols are diverse (Arcangeli et al., 2020), making it difficult to report similar or comparable data. Large-scale measurements of floating litter are currently limited to large objects (Lambert et al., 2020), although new technologies such as drones, aerial devices, and satellite observations show potential for improvement. Artificial intelligence and machine learning could further reduce the time and costs related to data acquisition and treatment (Sandra et al., 2023).

For seafloor litter, the implementation of the MSFD has advanced through regular trawl surveys dedicated to fish stock assessments of the MEDITS, IBTS and BITS initiatives (Spedicato et al., 2019; Barry et al., 2022). However, there are important questions regarding the sustainability and relevance of these surveys. These studies are limited to trawlable areas and do not consider shallow, deep-sea waters or rocky bottoms (Canals et al., 2021). The limited catchability of litter and the need for harmonization of procedures among different European programs also present challenges. New approaches, such as monitoring by NGOs and the use of remotely operated vehicles (ROVs), have been tested and offer potential solutions for expanding seafloor litter monitoring. Although this comes with the potential drawback of covering much smaller areas compared to monitoring based on trawling.

For microplastics, (uncoordinated) assessments in MSFD regions are widespread for surface waters, but measurements on beaches and in sediments are limited (Aliani et al., 2023). Analytical limitations and recurrent contamination hinder accurate measurements, and current protocols cover only microplastics larger than 300 μm. Currently, marine monitoring indicators that focus on larger size classes of microplastics are regarded as more robust for marine monitoring, e.g., for floating microlitter >300 μm and >1 mm on shorelines and when ingested by biota, and are identified as primary indicators (MSFD, 2023). Subsequently, monitoring of smaller size classes of microlitter/plastic is regarded as an option. The baseline levels and thresholds for GES characterization of microplastics are lacking. Efforts are being made to optimize strategies and develop appropriate indicators for microplastic ingestion, including proposals for representative species such as mussels and fish.

For regular monitoring within MSFD, measurements of marine litter ingestion are limited to larger size classes of microplastics above 1 mm and mesoplastics ingested by sea turtles and seabirds such as northern fulmars in specific sea regions (Galgani et al., 2022; Kühn et al., 2019). No indicator species have yet been identified to meet the criteria in the Baltic and Black Seas. Measurements of smaller size classes of microplastics in biota are also expensive and challenging, requiring improved protocols to avoid technical biases (Vanavermaete et al., 2024).

The thresholds for GES regarding ingestion by fulmars were determined by OSPAR and then by MSFD (Kühn et al., 2022). Discussions for sea turtles have been made within the EU projects INDICIT I & II (Darmon et al., 2022), but validation by the RSC is necessary. New approaches and species, such as mussels and fish (Kühn et al., 2019), are being considered for improving microplastic ingestion monitoring.

Entanglement is a significant impact of marine litter, especially due to abandoned, lost of otherwise discarded fishing gear (ALDFG). Indicators for entanglement have been included in the MSFD, focusing on specific types of litter affecting species and using prevalence evaluation. Stranding networks provide data for evaluating the entanglement of large vertebrates, but there are limitations in their interpretability due to their low prevalence and scientific constraints. New technical approaches, including the use of drones, are being explored (Claro et al., 2019). Additionally, the harm caused to benthic species is being assessed through visual observations or remotely using ROVs or submersibles (Galgani et al., 2018). The use of indicators for dead and entangled seabirds such as northern gannets (*Morus bassanus*), in which plastics are regularly observed to be incorporated into nests in major colonies, has been proposed as a secondary indicator of harm (Votier et al., 2011; O'Hanlon et al., 2019).

Data management for marine litter in Europe and reporting from each MS in their own language is still in its early stages. Currently, utilizing the EMODnet data infrastructure, its National Oceanographic Data Centers network (Molina Jack et al., 2019), and data transfer from other databases (e.g., ICES) has supported the collation of data from MS. Data tools and visualization are continuously being improved. The management of impact data is organized at the national level, but harmonization at the European level is needed. Data management must provide a harmonized common framework for data reporting but cannot fix misalignment or heterogeneity due to the lack of comparable monitoring methods.

Future developments in MSFD monitoring include seafloor litter video data collection, monitoring of microplastics in sediments, and floating macrolitter. Baselines and thresholds are being defined for harm indicators, but validation within the MSFD is needed. The translation of data from the particle basis to the weight basis is also necessary for small μm size ranges to harmonize data from larger-scale monitoring initiatives (e.g., global monitoring).

Finally, as it is difficult at this stage of development to determine how Artificial Intelligence (AI) will contribute to GES assessment and monitoring, its application cannot be analyzed in detail at this time. However, as the constraints and limitations of its large-scale application will likely be removed in the next few years, AI should be considered for future monitoring plans for marine litter (Politikos et al., 2023). The introduction of AI for microplastic monitoring and assessment may also support long-term data acquisition (Zhang et al., 2023) and compensate for the unavoidable bias that is present when manually separating and sorting microplastics, as well as interpreting spectra and data with current methods (Lusher et al., 2018; Phan and Luscombe, 2023).

5. Priorities

In the context of the MSFD, and based on recent accomplishments, the MSFD marine litter monitoring system is still in the process of being implemented and should take a few years to become fully operational. All recent developments, such as Reproducible Analytical Pipelines (RAPs) and Technological Readiness Levels (TRLs, Aliani et al., 2023), must be considered, and robust and synthetic approaches must be used to assess the maturity of each step of plastic monitoring. Within this context, several priorities need to be recognized.

A good understanding of the spatiotemporal heterogeneity of litter and its implications for survey design and replication, along with subsequent consequences for statistical power and robustness, is necessary (Haarr et al., 2022). Moreover, the systematic search for litter accumulation areas is redefining the monitoring strategy of different indicators. The development of recent methods to locate accumulation zones, especially on beaches using UAVs (Deidun et al., 2018; Fakiris et al., 2022) or traditional and systematic approaches (GESAMP, 2019), would allow for better specification of the areas to be monitored while also considering other constraints such as anthropogenic pressures, sources, and local-scale coastal currents. As an assumption of most statistical tests is an equal probability for all members of a population to be selected for sampling, it is also necessary to consider what is to be defined as the "population" for which one wishes to extrapolate and make inferences (e.g., entire coastline of a country, sandy beaches only) and whether potential sites within this population could be randomly selected.

Despite their questionable resolution in coastal areas due to numerous drivers and interferences, prediction models should be considered when identifying areas for monitoring. Currently, there are several studies and models examining plastic pollution sources, circulation, and sinks in the European oceanic environment (Van Sebille et al., 2020), but there are no large-scale European-specific models available for the marine environment.

The lack of data on the inputs of litter and microplastics to European waters is recognized as a knowledge gap (González-Fernández et al., 2021). Projects focusing on monitoring litter and microplastics in watersheds and water bodies flowing into Europe should be prioritized and will contribute to understanding freshwater sources, sinks, and circulation of litter and microplastics at sea.

The selected sources of marine litter, such as litter from fishing activities, are not always considered in monitoring programs (Ronchi et al., 2019). Existing data and possible new data collection schemes, such as permanent observers onboard fishing vessels, could support a new approach for assessing lost fishing gear on a monitoring basis (Garcia Alegre et al., 2020).

Assessing and better understanding the inputs of microplastics are necessary to advance a comprehensive understanding of the sources of microplastics in EU waters and inform reduction actions. Two particular examples include the release of microplastics from WWTPs and atmospheric fallout from urban centers to remote sites at sea. Both should be assessed and included in oceanographic and atmospheric particle transport models.

The quantities of marine litter inputs could be considerable during extreme events, as quantities from a single event such as the tsunami in 2011 can be on the same order of magnitude as the normal annual inputs of plastic into the World Ocean (Carlton et al., 2017). Accidental inputs of marine litter during extreme events and their balance compared to regular inputs need to be assessed, especially considering common cascading in the Mediterranean Sea (Canals et al., 2006) and regular storms in EU waters.

The rafting of species on debris at sea is a priority issue in terms of impacts. This could be addressed throught the development of an indicator to monitor these phenomena and associated risks. An inventory of species found settled on marine litter in various EU regions, including species that may cause risk, should be considered (Rech et al., 2016; Pasqualini et al., 2023).

6. Update of existing monitoring

Refining or implementing the existing monitoring scheme, optimizing protocols and sampling strategies, understanding litter heterogeneity, considering prediction models, addressing data gaps, assessing accidental inputs, and monitoring species transport on plastics are crucial for advancing comprehensive monitoring systems for marine litter within the MSFD. The monitoring strategy within the MSFD guidelines currently aims to cover all important environmental compartments, including marine waters, sediments, beaches/shorelines and biota such as invertebrates, fish, seabirds and/or turtles; All with sufficient data coverage and comparability. These compartments are complementary, and eliminating measurements in some of them is not logical from scientific and environmental perspectives. Understanding the relative importance and significance of measurements in each compartment is crucial, especially as the majority of marine litter is found on the seafloor, leading to significant impacts such as entanglement, habitat changes and impacts on fisheries. Comparatively, litter on beaches and floating at the ocean surface have lower quantities but different implications. Although they are easier to obtain and have considerable interactions with litter in nearby other compartments, beach litter measurements may be limited in representativeness in regard to what actually occurs in the sea and may have less impact on the marine environment. In addition, it should be noted that these measurements also include non-marine litter inputs from adjacent terrestrial areas extending beyond the marine environment, especially when urban or peri-urban beaches with many beach visitors are included as part of the monitoring strategy. On the other hand, analyses performed during beach litter surveys can provide more detailed information on litter compositions relevant for assessing litter origins and pathways and thereby also for identifying litter sources and mitigation measures.

While surface measurements of marine litter may appear sparse and quickly dispersed, the impacts are substantial, including frequent entanglement, ingestion of litter and microplastics by marine organisms, the rafting of species at risk over long distances (e.g., pathogens), and effects on navigation and fishing (UNEP, 2021). These measurements not only have environmental implications but also carry political consequences and contribute to discussions on transport and transboundary issues prevalent in Europe. Therefore, a comprehensive and streamlined monitoring approach should be optimized for the future, ensuring that measurements in certain compartments are not disregarded, even if their full implementation may take several years.

The item list recommended for EU MSFD monitoring was recently updated and extended with several litter items, so the monitoring list now covers 183 different litter items in total (Fleet et al., 2021). Additional categories, e.g., single-use plastic (SUP) items, including face masks and gloves in relation to the COVID-19 pandemic, had to be included locally to assess their consequences and adapt reduction measures accordingly. Focusing on specific categories that correspond to particular activities or impacts is also important. For instance, monitoring fishing gear or lost/abandoned nets may be relevant in certain regions with active fishing grounds. Similarly, specific monitoring of SUPs aligns with EU policies and reduction measures that require evaluation of their effectiveness. For this reason, having lists of item categories that properly manage, in a hierarchical way, the surveyed materials are crucial to be able to go from general/raw categories to more fine-grained considerations (material→use→ specific item). This will also avoid the "trap" of too generic categories such as "other" classifications, which can lead to non-useful and unmanageable results. Updated trend assessments have recently been described by OSPAR (2023) and HELCOM (2023), but further developments should optimize existing schemes based on these recommendations. Threshold levels may bel used for the evaluation of GES and adopted as targets, considering the challenges with transboundary transport, especially in countries and subregions where floating litter tends to accumulate on shorelines because of dominant ocean and wind currents.

7. Future monitoring

Monitoring is made of several components including the evaluation of quantities and trends, harm, data management, and regular assessments of the efficiency of reduction measures. This also includes the possibility of matching sampling frequencies of existing programmes to consider potential seasonal and interannual patterns.

7.1. Quantities and trends

The available data on litter and microplastics in different environmental compartments are unbalanced and limited (Haarr et al., 2022; Tia et al., 2022). In addition to existing monitoring methods, further coordinated efforts are needed to monitor and research the sources of litter and microplastics. A suite of monitoring approaches can be used to better assess marine litter quantities, evaluate trends, and track the effectiveness of actions (summarized in Table 2). These include (1) an extension of beach litter monitoring to address accumulation areas, (2) the inclusion of smaller size classes of microplastics >20 μm in sediments, (3) the linking of data with reduction measures, and (4) the refinement of data collection and management schemes.

Regarding sources and quantities, atmospheric dry and wet deposition rates of microplastics, particularly microfibers, lack data from remote as much as coastal marine regions. While the revised urban wastewater directive will consider regular monitoring of microplastics in WWTPs, a similar situation occurs for the presence of microplastics in both effluents and sludges. Furthermore, riverine inputs of litter and microplastics could be scientifically and technically more easily monitored. This requires coordination between the MSFD and the Water Framework Directive, with amendments planned to consider microplastics monitoring in freshwaters. Furthermore, fishing gear, especially nets, poses significant harm to marine ecosystems (GESAMP and Gilardi, 2021), necessitating monitoring of their impacts. Local or regional sources such as mariculture and aquaculture areas, shipping lanes, and tourism areas should be considered to address specific types of litter and initiate targeted reduction measures.

7.2. Harm for species

In addition to trends and monitoring, there is also a need to monitor the effects of litter and microplastics. However, we recognize that to assess these effects, programs need to be initiated to collect data. Monitoring the impacts of litter on fauna depends strongly on the availability of indicator species to measure the prevalence and effects of litter ingestion and litter entanglement. These effects can be monitored within a multispecies approach to cover the field of impacts linked to both the diverse types of litter of varied sizes (microparticles and macrolitter) and nature (plastics, metal, glass, etc.) and to the varied ways of life (sedentary, benthic, necto-benthic, pelagic, aerial) and feeding (detritus-eaters, suspension feeders, omnivores, carnivores) of the species that interact with it. The multiplicity of approaches needed to take this variability into account thus requires the use of many target species, and this is only possible if infrastructures crafted using diverse skills are in place. Monitoring can only be performed gradually, stage by stage, according to the degree of maturity of the indicators. Table 3 below summarizes the current MSFD descriptors and the proposed recommended methods and/or modifications.

Table 2
Possible extensions recommended for existing MSFD monitoring of marine litter and microplastics.

Environmental Compartment	Possible developments for monitoring
Beaches/shorelines/ mesoplastics	Beach/shoreline surveys focus on macrolitter. Expanding beach/shoreline monitoring will greatly improve the assessment of current litter pollution levels, and inform on mitigation actions. Beach/ shoreline monitoring can be done relatively readily by a variety of programs, including citizen science initiatives.
Accumulation areas along the coastlines	For beach litter, the number of sites monitored remains limited due to cost considerations. A systematic inventory of accumulation areas, including dumping sites and discharges on the coast, could complement the existing monitoring. This approach will make it possible to obtain an inventory of European priority areas requiring targeted reduction measures or removal. It is well adapted for citizen or participative science and the management of protected areas, allowing precise location of clean-up zones by municipalities, managers, NGOs or citizens.
Marine sediments/ microplastics	Microplastics in Marine sediment have different distribution and compositional patterns than surface waters (Maes et al., 2017), and measures of quantities are more stable over time and geographically. Knowing that research can improve methods and their reliability for small particles, implementation of microplastic monitoring in sediments seems to offer potential for relevant GES assessments and trend analysis.
Linking data with reduction measures	Monitoring may focus more on abundant litter items in several Europe regions, and/or those that are targeted by management measures. These include Abandoned, lost, discarded and abandoned fishing gear (ALDFG/ghost gear) and Single Use Plastics. The Commission Decision on indicators and guidance for GES assessment must include these categories, upon agreement by the formal groups (EU-TGML, WGGES and MSCG).
Data management	The ongoing experiences for the generation and update of the EU baselines in collaboration with EU-TGML for beach litter, seafloor trawling and now also floating and sediment microlitter can be a good starting point to evaluate similar processes for other matrices, type and sizes of litter. The use of common vocabularies and relevant sets of metadata describing the measured data quality and relevant features (e.g. survey types: MSFD monitoring, cleanings or citizen science data …) of datasets can ensure reliability and accessibility of data over long term
Reporting for the MSFD	MSFD reporting for descriptor 10 is currently done on a national basis. Taking advantage of the work done through EMODnet, will allow the storage of all MSFD D10C1 and D10C2 data, based on "Fair" principles (Partescano et al., 2021). While data collection remains to be organized at the EU level for other criteria on Harm (D10 C3, D10C4). European scale data management systems may serve for pan-European assessment of marine litter, providing EU scale results, maps and comparison of data.

Concerning harm, monitoring of litter ingestion in beached fulmars is currently in operation but is limited to a specific subregion and focuses on deceased individuals with unknown causes of death. Research should be expanded to include other species to examine the effects of plastic, microplastics, and plastic-derived contaminants. Biomonitoring that focuses on deceased individuals comes with inherent bias but is also preferable to the use of live individuals in terms of biomonitoring and associated ethical constraints. Furthermore, non-lethal sampling methods should be incorporated. In addition to fulmars and sea turtles, other species, such as certain fish and mussels, could serve as potential indicators for measuring the impact of microplastics, as regional

Table 3
A summary of the current MSFD Descriptors and the proposed recommended methods/changes/modifications. Priorities are given by timeframe and colors (Green = short term; blue = medium term; orange = long term).

MSFD Criteria / Indicator	Actual situation	GAP	Proposed recommended methods/changes/modifications	Timeframe
D10C1 (beach litter)	Visual survey	Automation, number of sites, accumulation areas (high deposition or retention rates)	Drone applications/ automatic classification of debris	Medium/long term
D10C1 (floating)	Visual surveys	Limited sampling, automation	Encourage Member states to implement monitoring of floating litter, use new methods (e.g. drones, deep learning)	Third MSFD cycle (2024-2030)
D10C1 & C2(beach and floating, microplastics)	Visual surveys	No consideration to riverine / coastal WWTPs or atmospheric inputs	Implement monitoring if riverine /WWTPs inputs of litter (in estuaries), coordinate with WFD. Evaluate atmospheric inputs	Third MSFD cycle (2024-2030)
D10C1 (floating and seabed)	Visual and trawling	Destructive sampling, No specific monitoring of ALDFG	Develop imaging tools and automated data collection, satellite/acoustic detection of tagged Fishing gear to limit losses and favour easy recovery.	Long term
D10C1 (sea bed)	Different List of litter categories	Seabed list of categories is different from the new EU-TGML joint List	Harmonisation of lists/ formalized conversion table is needed	Started / short term
D10C1 (floating and seabed), C2, C3 (sea turtle)s		No baseline and thresholds for floating litter, sea bed, Microplastics, SUPs and Fishing gear	Define baselines and thresholds for floating litter, SUPs and fishing gear to monitor the efficiency of reduction measures, strengthen the data collection and analysis system, the definition of baseline and threshold levels must be defined by Regional Sea Conventions	Third MSFD cycle (2024-2030)
D10 C1/New indicators/ criterion		Specific types of Litter are not monitored	The monitoring of lost containers in European waters, or collection of data on Lost fishing gear by observers on board fishing vessels is easy to implement	Medium/Long term
D10C2 (microplastics)	No monitoring of microplastics in sediment and beaches	Critical knowledge and monitoring gap, while sediment is a sink for microplastics	Implementation of a sediment microplastic dedicated monitoring, ideally coupled with the monitor of chemicals. Beach microplastics is more complex	Short term
D10C2 (microplastics)	No automated methods, No monitoring of small microplastics/nanoplastics	Large-scale assessments need automation, presence of nanoplastics is unknown	Reinforce research on automation (e.g. microfluidics) for monitoring of micro and nanoplastics)	Medium term, long term for nanoplastics
D10C3 /microplastics	No existing monitoring of	Analytical methods must be improved for selected species	MSFD has developed protocols for fish and mussels that will have to be tested on a pilot scale.	Third MSFD cycle (2024-2030)

	ingested microplastics			
D10C3 & C4/ Stranded organisms	Several species of top predators successfully used for assessment of ingestion/entanglement	opportunistic use of stranded networks is possible, but must be limited to regions at risk	Better defining the areas to be monitoring remains a challenge with a need for an EU scale inventory of species-specific sampling sites. Nest incorporation of litter by seabirds also provide a good indicator of risk of entanglement across EU waters. It has been successfully tested (review in TGML, 2023) and should be further implemented at a larger scale	Medium term
D10C4/ Interactions litter -invertebrates	No existing monitoring	Strong potential to monitor the interactions between benthic invertebrates and Marine Mitter	Monitoring must focus on specific areas (e.g. MPA, fishing grounds).	long term
D10/New indicators/	No record of rafted species at risk	Collection of data on rafted organisms, their possible toxicity and mode of invasion.	A dedicated plastic database collecting information on the colonization of plastics will provide historical records, evaluate trends and support risk assessments.	Medium/long term
Data	No harmonization of large scale databases	Global monitoring needs harmonizations or data and coordination	Better Link EU MSFD databases with databases from Regional Seas Conventions (ODIMS, DATRAS, INFORAC, etc.), also with international databases (G20 GOOS observing system, UNEP digital platform)	Medium term

programmes already monitor contaminant levels and may consider adding litter and microplastics to their efforts. Combined sampling and assessment will also reduce the number of individuals needed for monitoring. Collaboration with existing stranding networks is also recommended for monitoring marine mammals (e.g., Lusher et al., 2018). With respect to entanglement, efforts have been made to establish data collection systems for the South Atlantic and Mediterranean regions, but further work is needed to strengthen the system and broaden its coverage. The monitoring of entanglement by marine litter has been successful in assessing top predator species, and nest incorporation of litter by seabirds can be implemented on a larger scale (TGML, 2023). Epibenthic communities have the potential to monitor entanglement trends by marine litter due to their characteristics and distribution together with strong interactions with litter (Galgani et al., 2018; Angiolillo et al., 2021), reducing the risk of misinterpretation due to possible interactions with active fishing gear. Monitoring should focus not only on specific areas such as marine protected areas and fishing grounds but also near river mouths or WWTP outlets. Furthermore, data management system development will be necessary to establish baselines and thresholds for entanglement within the next cycle of MSFD (Galgani et al., 2023).

Transoceanic rafting of biota on litter, primarily plastics, is harmful and has become a concern, and there is a need to record the settling of species on marine litter and assess potential risks. The data collected should include information on the microbes and other species that colonize plastics and are transported by them. Sharing data through a dedicated plastics database and establishing links with existing databases on invasive species and marine litter would be beneficial. This approach would support historical records, trend evaluation, and risk assessments while integrating with other descriptors under the MSFD.

7.3. Methods and new data collection schemes

In terms of monitoring, the needs for ocean-wide data, automation of methods, cost efficiency and potential new tools are numerous. However, the need for regular, harmonized reporting and assessments of impacts on the environment and in support of management limits the application of new technological developments for monitoring purposes. Continuous flow-through microlitter sampling has been successfully tested, validating ferrybox technology for large-volume and surface sampling of microplastics (e.g., van Bavel et al., 2020). Upscaling this approach requires consideration of monitoring context, defining limits, and evaluating the increase in available data. Harmonization issues may arise when comparing subsurface and surface samples (Zhdanov et al., 2023). Direct measurement of microplastics using microfluidic approaches could complement this method, enabling large-volume continuous sampling (Higgins and Turner, 2023).

Aerial drones or unmanned aerial vehicles (UAVs) provide new opportunities for marine litter monitoring and the collection of high-resolution temporal and spatial data. UAVs are flexible and smaller in size than satellite imagery, allowing image capture under cloudy conditions and in narrow areas with higher spatial resolutions. This enables specific information collection on recorded surfaces. Within the EU MSFD, UAVs have the potential for cost- and time-efficient monitoring of large items, expanded spatial coverage, monitoring of fragile or inaccessible sites, and providing maps of litter abundance and distribution, particularly in hotspots (Escobar-Sánchez et al., 2020). They can also aid in monitoring the entanglement of large organisms stranded on shores or in remote areas (Claro et al., 2019). Equipping UAVs with hyperspectral sensors and pairing them with machine-learning applications supports automated identification and mapping of marine litter, provided that adequate accuracy can be demonstrated through field validation tests. Conducting a thorough analysis of the literature and pilot-scale monitoring experiments is recommended to evaluate the strengths and limitations in the context of MSFD monitoring. This approach could also contribute to the development of effective methods for marine litter collection and disposal.

If mandatory, and in addition to targeted retrieval efforts, the tagging of lost or entangled fishing gear, known as derelict gear (nets, traps, etc.), could support remote detection and location of litter from fishing through various means, including satellite tagging and acoustic sensor (GESAMP, 2019). The EU's consideration of mandatory tagging of fishing gear under the Zero Pollution Action Plan could provide new data to support monitoring of abandoned, lost, or discarded fishing gear (ALDFG) and assess the effectiveness of reduction measures.

The technological readiness level (TRL) approach could be simply applied to entire full plastic monitoring guidelines. In addition, reproducible analytical pipelines (RAPs) should be used to identify the best practices needed. to ensure that the coding pipelines and data processing are standardized, quality controlled and reproducible. As mentioned by Aliani et al. (2023), if applied singularly to each step in an RAP, it has the potential to greatly improve and accelerate the selection, evaluation, and adoption of large-scale plastic monitoring programmes. This approach is being implemented to support the monitoring of surface microplastics (Primpke et al., 2022), sea floor litter within the ICES region (Sandra et al., 2023), and harm within the MSFD (Vanavermaete et al., 2024).

Although not included in MSFD Descriptor 10 but Descriptor 8, the measurement of chemical contaminants related to marine litter is important due to associated risks. While chemical pollutants may be carried by plastics through adsorption from surrounding seawater, the intentionally added components of plastics (e.g., additives, plasticizers, dyes) must also be considered, especially considering their relatively high concentrations. Technological advancements allow for more accurate measurements and a better understanding of the cycling of these compounds. The integration of common and toxic compounds (e.g., phthalates) into the monitoring of Descriptor 8 (chemical contaminants) should be encouraged.

Additional data can be included in the MSFD if its collection is simple, informative, and meets quality control and harmonization requirements. Monitoring lost containers in European waters or collecting data on lost fishing gear by observers on board fishing vessels, which are already in place in Europe, provides necessary data to evaluate trends of specific items and prevent inputs into the marine environment. These monitoring modalities should be understood from a long-term perspective and aligned with International Maritime Organization plans. Finally, in addition to other sources of marine litter data, reflection on the organization of data collection and storage is necessary.

8. Recommendations

To support the current and future phases of monitoring for Descriptor 10 (Marine Litter) under the Marine Strategy Framework Directive (MSFD), the present work discussed the actual scientific and technical basis of monitoring and identified gaps and drawbacks in the existing approaches. Despite constraints, a balance must be found between what is possible, necessary, and beneficial and the associated risks (Lusher and Primpke, 2023). Monitoring Descriptor 10 on Marine Litter is one of the most accessible and least expensive within the MSFD, often relying on opportunistic approaches. Its implementation is expected to occur due to social demand and should be integrated into global initiatives such as the International Marine Debris Observing System (Maximenko et al., 2019), the G20 initiative (Isobe et al., 2021) and UNEA's binding international agreements (UNEA 5.2, Resolution 14 from UNEP, 2022), which all contribute to the specific objectives of the ocean decade, particularly the Sustainable Development Goal (SDG) 14.1.1 on plastic pollution.

To establish an effective long-term monitoring network, recommendations are proposed for the improvement and optimization of existing systems, the development of new approaches, and the integration of monitoring protocols and communities across Europe. The monitoring of marine litter in Europe is currently the most advanced network globally and plays a key role in environmental protection. Addressing plastic pollution requires quality data and optimized data collection schemes, as well as international cooperation and continuous dialog to allow cross-regional development. Preliminary experiences and ongoing integration efforts can serve as a starting point for addressing other emerging topics.

Several monitoring recommendations must be considered as a matter of priority (Table 3), taking into account the ability of European countries to quickly implement various monitoring approaches through existing programs. These recommendations cover existing monitoring schemes and programmes, sources and inputs to the marine environment, monitoring of impacts, and new approaches with new data collection schemes. To improve coverage, all environmental compartments for litter should be considered, including atmospheric, sediment, invertebrate, and fish compartments for microplastics. The collection of information and monitoring approaches for entanglement/strangling (D10C4) should be organized, with a focus on sensitive species through experimental monitoring and mobilization of stranding and observation networks. The potential of surface and underwater observation campaigns, shallow diving, submersibles, and remotely operated vehicles (ROVs) for entanglement/strangling observation of affected species must be assessed. Coordinated pilot experiments should be conducted to improve data collection and focus on prevalence, risk area identification and mapping, and rationalization of observation procedures based on existing arrangements.

9. Conclusion

The growing concern and increasing interest in marine litter and plastic pollution necessitate a comprehensive and coordinated approach to monitoring and mitigation. The Marine Strategy Framework Directive (MSFD) and various regional conventions provide essential frameworks for assessing and addressing these issues. Despite the advancements in monitoring marine litter across Europe, there remain significant challenges and gaps that need to be addressed. Effective monitoring programs are critical for evaluating trends, identifying impacts, and informing policies aimed at reducing marine litter. The diversity of methodologies and the lack of standardized protocols pose substantial challenges to the harmonization and comparability of data. This complexity underscores the need for more coordinated efforts, refined strategies, and improved technologies in monitoring practices.

Future monitoring efforts should focus on expanding coverage, incorporating new indicators, and addressing methodological constraints to enhance data quality and comprehensiveness. Emerging technologies such as UAVs, AI, and improved analytical pipelines offer promising solutions to some of these challenges. Additionally, addressing specific sources of marine litter, such as fishing gear and microplastics from WWTPs and atmospheric fallout, is crucial for a holistic understanding and effective mitigation. Ultimately, the success of marine litter monitoring hinges on international cooperation, continuous dialog, and the integration of efforts across different regions and sectors. By prioritizing the development of harmonized protocols, improving data management systems, and leveraging technological advancements, we can build a robust monitoring network that supports sustainable marine environments and informs global initiatives against plastic pollution.

CRediT authorship contribution statement

Francois Galgani: Writing – original draft, Validation, Supervision, Resources, Methodology, Investigation, Conceptualization. **Amy L. Lusher:** Writing – review & editing, Validation, Project administration, Funding acquisition. **Jakob Strand:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis. **Marthe Larsen**

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Declaration of competing interest

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

Data availability

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

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