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Setting the course: aligning European Union marine pollution policy ambitions with environmental realities

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Pollution in coastal and marine waters is a global challenge that transcends national boundaries, affecting interconnected seas, the ocean and broader ecosystems. Addressing marine pollution requires policies that encompass not only the marine domain but the entire ecosystem, including human societies. Therefore, a comprehensive and integrated governance approach, linking land-based sources to marine environments, is essential for effective pollution management and mitigation. This study assesses the current environmental status of persistent, long-lasting and emerging pollutants (PCBs, excess nutrients, microplastics, PFAS, and underwater noise) and cumulative effects of pollution, and compares these with the set European Union (EU) environmental goals and ambitions. A systematic review of EU policy documents reveals that several targets are unclear, arbitrary, and often unattainable, limiting the effectiveness of current strategies. This paper presents five actionable recommendations to strengthen marine environmental policy, emphasizing the need for better alignment between EU ambitions and environmental realities. To enhance EU pollution policies, it is crucial to reinforce regulatory frameworks, ensure the effective enforcement of existing legislation, foster collaboration across sectors, and empower citizens and NGOs. Additionally, integrating health and pollution policies, ensuring public access to pollution data and knowledge, and establishing international leadership in pollution efforts are key for making informed decisions and achieving ambitious pollution reduction targets.

KEYWORDS

source to sea governance, attainability of EU environmental goals, regulatory framework, multi-dimensional approach, current environmental status, good environmental status (GES)

1 Introduction

Pollution represents a widespread threat to coastal and marine waters worldwide, often transcending geographic, legal, and jurisdictional boundaries. All seas and oceans are interconnected (IOC-UNESCO, 2020), and the marine environment is inextricably linked to the broader environment, underscoring the universal nature of the problem. The most effective policies aimed at addressing marine pollution from an environmental perspective are those that acknowledge this interconnectedness and go beyond the marine domain by encompassing the entire ecosystem, including integration of risk perception and other socioeconomic aspects (Tocco et al., 2024). The development of such policies can be guided by a source-to-sea framework, which considers the emission sources and pathways of pollution across air, land, freshwater, and marine environments, while also addressing the shared or interconnected responsibilities of the authorities and policies. The growing understanding that 'the Earth behaves as a system in which oceans, atmosphere and land, and the living and non-living parts therein, are all connected' (Steffen et al., 2005), has led the European Union (EU) to adopt comprehensive frameworks such as the Zero Pollution Action Plan (ZPAP; COM (2021) 400), a cornerstone of the EU Green Deal (COM (2019) 640) despite the fact that the ZPAP itself is not a legally binding instrument imposing mandatory obligations on Member States (MS). However, a limited understanding of how ecosystems are interconnected, fragmented governance and management arrangements across the source-to-sea continuum due to the transboundary nature of pollution, coupled with jurisdictional limitations, collectively hinder effective source-to-sea governance and policymaking (Granit et al., 2017; Tocco et al., 2024; Cowan et al., 2025).

Marine pollution management is further challenged by the high number, diversity and complexity of pollutants (Dahms, 2014), as well a limited understanding of their cumulative impacts and how this varies under changing climatic conditions (Ferraro and Failler, 2020). Despite advances in our understanding in recent decades, many uncertainties remain regarding the scale and type of pollutant emissions to the environment, their environmental impacts at specific concentrations and the effects derived from their combined or aggregated interactions (Plaza-Hernández et al., 2021). Each type of pollution (e.g. chemical, particle, noise, nutrient) also poses specific hazards, with varying levels of scientific understanding and ecological implications. Historical contaminants, such as polychlorinated biphenyls (PCBs), can differ significantly in their characteristics, sources and pathways, impacts, and management strategies from emerging pollutants like per- and polyfluoroalkyl substances (PFAS) for example. PCBs, heavily restricted in the EU since the 1980s (76/769/EEC; 85/467/EEC; Stockholm Convention on persistent organic pollutants; Melymuk et al., 2022), could therefore potentially serve as a historical benchmark for policy success, whereas PFAS represent an emerging threat where there are currently many unknowns (Klingelhöfer et al., 2024). However, it is also important to acknowledge the different nature of various forms of pollution, each of which often requires distinct management approaches. For instance, light and noise pollution exhibit fundamentally different dynamics when compared to chemical pollution. In the case of light and noise pollution, once the source is addressed or mitigated, the pollution itself ceases to exist almost immediately. This contrasts with the prolonged impact of certain chemical pollutants, which may persist in the environment for long periods of time even after the source has been reduced or eliminated; PCBs being a good example of this. This irreversibility of some chemical pollutant contamination and toxicological effects is one of three conditions—along with disruptions to vital Earth system processes and planetary-scale impacts—required for it to pose a planetary boundary threat (Persson et al., 2013).

Addressing these challenges requires an inclusive, source-to-sea governance approach that integrates diverse stakeholder perspectives, including policymakers, decisionmakers, scientists, industry actors, and civil society representatives (Mathews et al., 2019). The two recent European Commission (EC) recommendations, (EU) 2024/736 and (EU) 2024/774, highlight the critical role of stakeholder engagement and participation in the process of knowledge valorisation. Furthermore, the Better Regulation agenda (COM (2015) 215) provides the foundation for integrating citizens, businesses, and stakeholders into the EU's decision-making processes, ensuring that regulatory frameworks are transparent, inclusive, and responsive to societal needs. Stakeholder participation and engagement enhances transparency, fosters public awareness, and ensures that policies are informed by a science-policy-society interface (Agnew et al., 2023, 2022; Black et al., 2019a, 2019b; Kujala et al., 2022). In general, stakeholder participation is ensured by the EC through stakeholder consultations, public consultations, and established working groups (Devriese et al., 2023; COM (2015) 215), however the degree to which civil society and stakeholders are included and can engage varies across EU environmental, legal, and policy frameworks (Black et al., 2019b). A participatory policy approach is crucial for identifying relevant and feasible measures that are based on substantiated knowledge and scientific evidence, as well as subjected to rigorous evaluation to ensure their effectiveness in mitigating pollution. Stakeholder engagement in policy development must extend beyond superficial consultation processes to foster ownership and build trust, but moreover to

Abbreviations: BS, EU Biodiversity strategy 2030; CFP, Common Fisheries Policy; CJEU, European Court of Justice; DG, Directorate-General; EC, European Commission; ECHA, European Chemical Agency; EPR, Extended producer responsibility; EQS, Directive on the environmental quality standards; EU, European Union; FFS, EU Farm to fork strategy; GES, Good Environmental Status; MO, EU Mission Ocean - Restore our Ocean and Waters; MPs, Microplastics; MS, EU Member State(s); MSo, EU Mission Soil - A Soil Deal for Europe; MSFD, Marine Strategy Framework Directive; OSPAR, Oslo-Paris Convention for the Protection of the North-East Atlantic; PCBs, Polychlorinated biphenyls; PFAS, Per- and polyfluoroalkyl substances; REACH, REACH (Registration, Evaluation, Authorisation, and Restriction of Chemicals) regulation; SAPEA, Science advice for policy by European academies; SDGs, Sustainable Development Goals; UWN, Underwater noise; WFD, Water Framework Directive; ZPAP, EU Zero Pollution Action Plan.

improve the quality and relevance of the resulting policies (Black et al., 2019a). A truly participatory approach requires deeply embedding stakeholders in the development of policy from the outset, ensuring that their input is not only heard but also meaningfully integrated into decision-making (Bracken et al., 2015; Wesselink et al., 2011). Beside the added value of public engagement, public pressure also plays a role in encouraging compliance (Howard, 2017).

Beyond public pressure, the EU can assert legal action against MS for failing to achieve targets or comply with obligations outlined in its directives. The EU enforces compliance through a structured infringement procedure, as provided for under Article 258 of the Treaty on the Functioning of the European Union. Initially, the EC issues a formal notice to the infringing MS, outlining the violation. If the issue remains unresolved, the EC escalates the matter by issuing a reasoned opinion, demanding that the MS comply with EU law. Should non-compliance persist, the case may be referred to the Court of Justice of the European Union (CJEU) for judicial review. In the event of a ruling against the MS, the Commission can return to the CJEU to seek financial penalties, which may include lump-sum fines or daily penalties, continuing until the MS achieves compliance with the ruling. Examples of enforcement actions taken by the EU demonstrate the EC's commitment to upholding environmental legislation. In relation to Air Quality Directives (2004/107/EC; 2008/50/EC), for instance, the EU has frequently acted against MS that failed to meet air quality standards, such as limits on nitrogen dioxide (NO_2) or particulate matter (PM10). Notably, in 2021, the CJEU ruled against Germany, France, and the UK for breaching air quality limits (Press Corner, European Commission, 2021). Poland was fined €3 million in 2018 for persistent violations of air quality standards (Press Corner, European Commission, 2018). In 2015, a €40 million lump-sum fine was imposed on Italy for failing to meet Waste Management Directive targets, which was followed by daily penalties until the country complied with EU waste management legislation (CJEU, 2015). In the area of Water Framework Directive (WFD) compliance, both Greece and Spain faced legal actions for failing to meet water management requirements. For example, Greece was penalised for not establishing adequate wastewater treatment systems in certain urban areas (Press Corner, European Commission, 2019). Similarly, under the Habitats and Birds Directive, Ireland faced infringement actions for failing to designate Special Areas of Conservation and to protect habitats (CJEU, 2017). Finally, MS have faced scrutiny under the Renewable Energy Directive for not meeting binding renewable energy targets, though enforcement often involves corrective measures and fines rather than immediate legal action (Press Corner, European Commission, 2020). The EU network for the implementation and enforcement of environmental law plays a supportive role in this process, complementing the EU's enforcement mechanisms. The qualitative impacts of these enforcement actions are notable. They create significant pressure to enact reform, encouraging governments to expedite the implementation of EU directives. They also raise public awareness regarding the importance of compliance, sometimes igniting public and political debates (Press Corner, European Commission, 2018). Furthermore, such actions establish legal precedents, with CJEU rulings shaping binding interpretations of EU law and influencing future compliance across MS (Press Corner, European Commission, 2021). Overall, these enforcement mechanisms ensure the effectiveness of EU law, maintain a level playing field among MS, and support the overarching goals of the EU, including environmental conservation, public health, and sustainable development (CJEU, 2015).

This paper explores the factors influencing the effectiveness of EU marine pollution policies across multiple framework directives and EU Green Deal, highlighting the interconnections between these instruments. By examining both historical and emerging contaminants, this study assesses the alignment between EU ambitions and current environmental realities, and identifies critical gaps in scientific data and knowledge related to specific contaminants. These gaps are fundamental to understanding environmental risks and are therefore essential for setting meaningful, understandable, and measurable pollution targets. This approach, which focuses on the formulation of feasible and scientifically grounded environmental targets, can thus be seen as complementary to the recent assessment by the European Commission on the effectiveness of MS' Programmes of Measures under the Marine Strategy Framework Directive (MSFD) (COM (2025) 3 and the accompanying document SWD (2025) 1), which highlighted the need for improvements in both policy coherence and the effectiveness of the measures implemented. A key question addressed in this study is whether all knowledge gaps must be filled to enable effective action, or if addressing only some gaps is sufficient, or if the existing evidence base is already adequate to address the known hazards and risks. The analysis leverages the concept of post-normal science - recognising high levels of uncertainty, complexity, and societal debate - to navigate these uncertainties, recognising and reflecting the complexity of managing diverse contaminants with varying ecological impacts. Rather than just pinpointing gaps in policy or governance, actionable recommendations to enhance marine environmental policy are identified, offering insights for addressing cumulative impacts and fostering a more sustainable and interconnected management framework.

2 Methodology

2.1 EU policy mapping of marine pollution and cumulative effects

A comprehensive desktop study was conducted to compile an extensive range of European Union (EU) policy documents (e.g., regulations, directives, action plans, and integrated strategies), directly addressing on or strongly related to marine pollution. While an extensive range of documents were initially screened (n>145), a curated subset of the most relevant and representative regulations and policy instruments has been retained, based on the selection criteria of Table 1, and is presented in Supplementary

TABLE 1 Selection of pollutants, associated keywords, and narrative focus.

Pollutant	Keywords	Narrative Focus
PCBs	PCBs, CBs, polychlorinated biphenyl, polychlorinated compounds, POPs, PBTs, hazardous chemicals or substances, chemical pollution	concentrations of contaminants (PCBs, polychlorinated biphenyls, CB congeners, indicator or priority PCBs) in surface waters, seawater, sediment and biota
Excess nutrients	nutrients, eutrophication, nitrates and phosphate	nutrient concentrations in water, with a focus on dissolved inorganic nitrogen and phosphorus
PFAS	PFAS, POPs, PBTs, PFOS, PFOA, hazardous chemicals or substances, perfluoroalkyl chemicals, chemical pollution, chemicals of concern	concentrations of contaminants (PFAS, PFOS, PFOA & derivatives) in surface waters, seawater, sediment and biota
MPs	microplastics, micro-litter, plastic debris, marine litter	main focus on spatial distribution, but also considers the criterion ingestion
UWN	underwater noise, underwater sound	focus on two types of underwater noise: anthropogenic impulsive sound (impulsive noise) and anthropogenic continuous low-frequency sound (ambient noise)
Cumulative effects	cocktail of pollutants, mixtures, cumulative effects, synergetic effects, pollution of all kinds, all types of pollution	focus on the mention of cumulative effects in policy documents and possible suggestions on how to address them from a policy perspective

Table 1. The selection of case study pollutants reflects (i) a strategic focus on both historical and emerging environmental threats, (ii) the diversity of pollutant forms, and (iii) their distinct ecological and policy-related management challenges: PFAS, PCBs, excess nutrients, microplastics (MPs), and underwater noise (UWN). In addition, a detailed analysis was conducted on the concepts, vision, and potential tools outlined in current EU policies for their ability to manage the cumulative effects of multiple pollutants acting upon the marine environment. Each pollutant represents a unique category with specific hazard profiles (e.g. ecological risks), scientific understanding, and regulatory contexts:

- Classified as legacy pollutants and persistent organic pollutants (POPs), and representing a successful case study in environmental policy, PCBs have been heavily restricted across Europe since the mid-1980s, with Europe long regarded as a ‘world leader’ in addressing the risks associated with these chemicals (Stuart-Smith and Jepson, 2017). PCBs were used in lubricants and in electrical and hydraulic equipment. The historical context of PCBs offers potential lessons on best practices in environmental chemical pollution management (although some sub-regions are still in a poor status for hazardous substances in marine species linked to PCB contamination (COM (2025)3)), which could potentially be applied to the management of emerging chemical pollutants. In addition, PCBs are subject to long-range transport, so despite being banned in the EU, they may still reach it from regions where PCB use is not fully prohibited (Mulder et al., 2015).
- Excess nutrients, although a long-standing type of pollution, continue to be a significant environmental priority (Axe et al., 2022; HELCOM, 2022). Despite nutrients being essential for life and nutrient pollution being recognised for decades, excess nutrients continue to pose challenges due to the continuous input from ongoing land-based human activities, such as agricultural runoff and wastewater discharges (Grizzetti et al., 2021). Moreover, the current lack of universally effective mitigation measures further compounds their environmental persistence and associated management challenges, as also emphasised by COM (2025) 3 and the accompanying document SWD (2025) 1.
- PFAS are an emerging class of chemical pollutants with a vast diversity, comprising more than 4,700 individual substances (Glüge et al., 2020). Their unique properties (e.g., heat resistance, surfactant behaviour, and water repellency) have driven extensive industrial and consumer use (SWD (2020) 249; van Leeuwen et al., 2023), resulting in environmental pollution, and consequently, risks induced by their persistence to ecosystems and human health (Klingelhöfer et al., 2024). Despite increased regulatory efforts, significant knowledge gaps remain regarding their environmental impacts, long-term behaviour, and effective mitigation options.
- MPs are a form of emerging particulate pollution that has recently come to the forefront of scientific research and public discourse (Thacharodi et al., 2024). Their global and ubiquitous presence, as well as their high abundance in the environment has been documented by numerous studies (Eriksen et al., 2014; Jaikumar et al., 2025). Despite the research conducted so far, MPs remain challenging to monitor due to their varying sizes and sources, as well as their behaviour and transport mechanisms (Harris et al., 2023; Thompson et al., 2024). Furthermore, the presence of additive chemicals and non-intentionally added substances in plastic consumer products from which MPs derive, means that this class of pollutant represents both particulate and chemical pollution. MPs have recently been identified as a potential threat to both aquatic and terrestrial ecosystems (Harris et al., 2021; Nyberg et al., 2023). Recent research on MPs continues to provide strong evidence of their ecological and human impacts (SAPEA, 2019; Vethaak and Legler, 2021). Over the past six years,

there has been a notable improvement in the effectiveness of measures aimed at combating marine litter, with several MS implementing specific actions to tackle microplastic pollution (COM (2025) 3).

- The transient nature of UWN distinguishes it from persistent chemical pollutants, emphasising the importance of management strategies that focus on halting or reducing the source (COM (2025) 3), rather than dealing with long-lasting environmental residues (Merchant, 2019; Merchant et al., 2022; Trounce et al., 2024). Another aspect of UWN pollution is that the growth and advancement of the Blue Economy, with more activities taking place at sea, will likely give rise to certain external sources of noise, where achieving zero reduction is not a viable option.
- The cumulative effects arising from multiple chemical pollutant stressors acting upon an ecosystem is still very much a developing research field and our current understanding remains limited. The analysis aimed to evaluate how the EU addresses marine pollution as a complex mixture of pollutants and how it manages the associated uncertainties of governance. This approach recognises that pollutants do not act in isolation, instead interacting with each other in ways that lead to synergistic or compounding ecological impacts. The findings from this step will help identify policy gaps and limitations in managing cumulative effects, providing a baseline for further analysis and future work.

For each of the selected case study pollutant classes above, specific keywords were used to screen the policy documents (Table 1). The focus of the narrative review of EU legislation and policy informing documents for each of the compounds is also listed in Table 1. This policy mapping exercise mainly focused on European environmental policy, for which EUR-Lex served as the primary data source, supplemented by detailed searches for regulatory reports on the websites of relevant European institutions, e.g. EC Directorate-Generals (DGs), other EC platforms, and online search engines. To have a general overview and insights into the historical development of environmental policies, global major treaties addressing marine environmental issues (such as the Convention on Biological Diversity, United Nations Convention on the Law of the Sea, and International Convention for the Prevention of Pollution from Ships) and Regional Seas Conventions documents (Oslo-Paris Convention - Northeast Atlantic Ocean and North Sea, Helsinki Convention - Baltic Sea, Bucharest Convention - Black Sea, and Barcelona Convention - Mediterranean Sea) were considered as background information (Devriese et al., 2023).

The primary goal of the activity was to screen all the EU policy documents for relevant environmental targets or thresholds (meaning defined (numeric) objectives) related to the case study pollutants and cumulative effects. This process produced a refined shortlist of documents that reflect European ambitions, plans and intentions to address these pollution types. The identified policy targets (or thresholds) to address marine pollution were then analysed using the SMART criteria (specific, measurable, achievable, relevant, and time-bound; with emphasis on measurable and time-bound) and evaluated for attainability (achievability) and meaningfulness (understandability) (Doran, 1981; Cormier and Elliott, 2017; Van Herten and Gunning-Schepers, 2000; Wood, 2011).

2.2 Insights into the current environmental status

To gain insights into the current environmental status in European waters, the environmental assessments of the MSFD and WFD were consulted as a starting point, as well as the follow-up of the ZPAP. A narrative review of regulations and policy supporting reports and documents (by non-governmental organizations, intergovernmental organizations, institutions dedicated to ocean affairs, etc.: e.g. OSPAR Commission, the EC, the European Chemicals Agency (ECHA), EU Marine Board and SAPEA) supplemented the description of the current environmental status. The collected information is systematically aligned according to key concepts essential for assessing the current environmental status, including the existence of official monitoring programmes, the clarity of environmental targets and thresholds (e.g. in relation to the Good Environmental Status; GES), and their achievement status. Additionally, the availability of (credible) baseline data was examined, including the clarity of reporting and the use of harmonised methods, understanding the environmental risks and harms associated with measured contamination levels, and information on source emissions and transport into the environment.

2.3 Benchmarking between the current environmental status and the EU ambition

The aim of this benchmarking exercise is to assess the feasibility of achieving the environmental targets set by the European Union (EU), considering the ambitions outlined in the ZPAP. The evaluation focuses on two aspects of feasibility: understandability and attainability of the EU targets and thresholds. The main prerequisite for establishing quantifiable targets (defining the desired environmental status) is that there must be sufficient knowledge and data to assess the current environmental status and/or current source emissions, which is further evaluated and subjected to expert judgement by the co-authors. Finally, recommendations (stepping stones) have been formulated to highlight potential focal points to improve or advance policy, including its various components, to achieve more favourable outcomes for marine environment protection.

2.4 Integration of pollution into EU marine conservation and management frameworks

In addition to the mapping of marine pollution-related policies based on keywords (see above), a selection of foundational European Union (EU) legal texts and strategies was identified based on their relevance to marine conservation and spatial planning to assess their current provisions and mechanisms for addressing marine pollution. These included the EU Biodiversity Strategy 2030, the Birds Directive, the Habitats Directive, the Maritime Spatial Planning Directive, the Nature Restoration Law, and SWD (2022) 23. The MSFD and WFD are excluded from the scope, as they were already addressed in the former exercise. A keyword-based content analysis was conducted for each document. Specifically, the terms 'pollution', 'pollutant', 'contamination', and 'contaminant' were systematically searched to identify explicit references to pollution-related issues. Additionally, each occurrence was analysed to determine whether the legislation provided specific governance tools, actionable measures, set explicit goals, or referred to complementary legislation addressing pollution.

3 Results and discussion

3.1 Assessment of the EU policy ambition and current environmental status

3.1.1 What's the EU policy ambition and approach to tackle marine pollution?

3.1.1.1 Addressing the root cause

Some PFAS, particularly PFOS (perfluorooctane sulfonate) and its derivatives, have been regulated and restricted in Europe for over 10 years, currently under the Persistent Organic Pollutions (POPs) Regulation (EU) 2019/1021, implementing the provisions of the Stockholm Convention at the European Union (EU) level. The use and marketing of most PCBs has been restricted for over 30 years under Directive 96/59/EC. Continuing these efforts, the EU employs a source-focused strategy to address pollution, with the REACH Regulation (EC 1907/2006) targeting intentionally added MPs to products, as well as all non-essential uses of PFAS, and multiple restrictions on the use of PCBs. While PCBs are well-documented pollutants, further restrictions on their use continue to be implemented (Regulation (EU) 2019/1021). However, for more recently recognised forms of pollution, like PFAS, MPs, or UWN, regulatory measures and timelines are far less clear (Table 2). In general, in the framework of the MSFD, progress has been made in developing measures to further reduce both nutrient and chemical pollution, as well as in improving MS' actions to reduce underwater noise, although these efforts remain focused on knowledge gathering rather than mitigating pressures, as outlined in COM (2025) 3. In general, the EU is committed to an integrated approach that reduces environmental pollution, fosters a resource-efficient and sustainable economy, while strengthening ecological resilience (e.g. Green Deal COM (2019) 640, COM (2021) 240).

The EU is addressing the reduction of MPs through multiple policy frameworks, in particular via the REACH regulation but also through diverse strategies and action plans aimed at minimising the intentional use of MPs, as outlined in documents such as the Plastics Strategy (COM (2018) 28), COM (2020) 98, and COM (2021) 400, alongside the EU Mission 2030: Restore Our Ocean and Waters (Mission Ocean – MO). Additionally, the unintentional release of MPs is primarily tackled through COM (2018) 28, the Waste Framework Directive (2008/98/EC), and the MSFD (2008/56/EC), which focuses on all types of microlitter. Initiatives under the EU Green Deal (COM (2019) 640, COM (2021) 400, COM (2020) 380), and the EU Mission Starfish 2030 (EC, DG RTD 2020), alongside the MSFD, call for action on UWN. Additionally, the 2030 climate ambition (COM (2020) 562) and the Sustainable and Smart Mobility Strategy (COM (2020) 789) aim to reduce noise pollution by decarbonising maritime transport and establishing 'Emission Control Areas' to help achieve zero waterborne pollution. The EU aims to reduce PFAS pollution by setting emissions limits in waste management (86/278/EEC, EC/1013/2006) and industrial emissions (2010/75/EU), supporting the Chemicals Strategy for Sustainability (COM (2020) 667) and the ZPAP (COM (2021) 400). For nutrients, a long-standing source of pollution, there remains a strong need for source-directed approaches (COM (2025) 3). This is mainly guided by diverse directives (Directive 91/676/EEC, Directive 91/271/EEC, Directive (EU) 2016/2284, Directive 2010/75/EU), although a holistic nutrient management plan is being advanced through the Integrated Nutrient Management Initiative and Action Plan (COM (2021) 1000; COM (2019) 640; European Commission, 2022). A full overview of key EU policy documents related to addressing (marine) pollution is presented in Supplementary Table 1, including directives (n=21), regulations (n=9), decisions (n=4), communications (n=20), staff working documents (n=8), reports (n=6) and other (n=3). A comprehensive summary of relevant policy documents at the Regional Seas Conventions or global level is presented in Devriese et al. (2023).

3.1.1.2 Environmental directives

In terms of spatial coverage, the WFD and MSFD both apply in coastal and territorial waters, although the application of the WFD in territorial waters is limited to the chemical status of the water. For the objectives of Good Chemical Status, the WFD extends to 12 nautical miles seaward from the baseline. The MSFD also applies to these areas and addresses some additional aspects not covered by the objectives of the Good Chemical Status of the WFD, such as marine litter (Descriptor 10) (Bigagli, 2015). WFD assessments for the transitional waters are used for the MSFD assessment where relevant (e.g., Descriptor 5 on eutrophication), linking the WFD's Good Ecological Status or Good Chemical Status with the MSFD's GES. Concerning 'Contaminants' (relevant for PCBs, MPs and PFAS), the MSFD considers that GES is achieved when 'Concentrations of contaminants are at levels not giving rise to pollution effects', and for some pollutants (such as PCBs) the OSPAR environmental assessment criteria (EACs) are used ((Lyons et al., 2017; OSPAR, 2009, 2004; Vethaak et al., 2017; EU/

TABLE 2 EU environmental targets and timeframe for the selection of pollutants.

Pollutant	EU environmental policy	EU key target	Time-bound & status
PCBs	ZPAP	Not explicitly mentioned.	Not applicable
	REACH, POPs Regulation	Multiple restrictions; eliminate PCBs >0.005%, >50 ml in dielectric equipment by 2025.	Implemented
	MSFD, (OSPAR, WFD, EQS) based on OSPAR EAC	D8C1, D9C1. EACs for PCBs in water, sediment and biota are based on OSPAR thresholds. Threshold values for the sum of the indicator PCBs in diverse matrices (biota, sediment, water).	Implemented
Excess nutrients	ZPAP, (MSo, FFS, BS)	Reduce the use of nutrient losses by 50% while ensuring that there is no deterioration in soil fertility.	By 2030 (start: 2015)
	MSFD, (WFD)	D5C1 Nutrients concentrations in water (primary) - Nutrient concentrations are not at levels that indicate adverse eutrophication effects.	Cycle 2022-2027
MPs	ZPAP, MO	Improving water quality by reducing waste, plastic litter at sea (by 50%) and microplastics released into the environment (by 30%).	By 2030
	MSFD	D10C2 (Primary) - Spatial distribution of micro-litter: The composition, amount, and spatial distribution of micro-litter on the coastline, in the surface layer of the water column, and in seabed sediment, are at levels that do not cause harm to the coastal and marine environment.	Cycle (e.g. 2022-2027) once implemented
	MSFD	D10C3 (Secondary) - Micro-litter ingestion: The amount of litter and micro-litter ingested by marine animals is at a level that does not adversely affect the health of the species concerned.	Cycle (e.g. 2022-2027) once implemented
	REACH	Restriction concerning the intentional addition of microplastics to (consumer or professional use) products.	Preparation
PFAS	REACH, (ZPAP)	Restriction under REACH on all non-essential uses of the per- and polyfluoroalkyl substances (PFAS), preventing their emission to the environment	Preparation
	MSFD, (EQS, WFD)	D8C1, D9C1. Not mandatory under MSFD (voluntary compounds).	Cycle (e.g. 2022-2027) once implemented
	WFD, (EQS)	Threshold values (max. allowable concentrations) for inland surface waters.	Cycle 2022 - 2027
		Threshold values (max. allowable concentrations) for other surface waters and seawater	Cycle 2022 - 2027
UWN	MSFD, (ZPAP, BS)	D11C2 20% of the target species habitat having noise levels above the Level of Onset of Biologically adverse Effects (LOBE) not to be exceeded in any month of the assessment year, in agreement with the conservation objective of the 80% of the carrying capacity/habitat size.	Recently published (11/2024), next cycle
		D11C1 For short-term exposure (1 day, i.e., daily exposure), the maximum proportion of an assessment/habitat area utilised by a species of interest that is accepted to be exposed to impulsive noise levels higher than the Level of Onset of Biologically adverse Effects (LOBE), over 1 day, is 20% or lower (≤ 20%). For long-term exposure (1 year), the average exposure is calculated. The maximum proportion of an assessment/habitat area utilised by a species of interest that is accepted to be exposed to impulsive noise levels higher than LOBE, over 1 year on average, is 10% or lower (≤ 10%).	Recently published (11/2024), next cycle
Cumulative effects	ZPAP	Combined effects of all types of pollution mixtures turned out to be of a far greater concern to our health and environment than just looking at the individual substance.	Acknowledged (no specific instructions)

2017/848). Although PFAS are currently listed as priority hazardous substances, reporting through MSFD is on a voluntary basis (stated as voluntary compound). With 'Nutrients', the MSFD focuses on the effects of nutrient inputs (e.g. macrophyte communities, dissolved oxygen, harmful algal bloom events, chlorophyll a concentrations), with one criterion on the monitoring of nutrient concentrations to make sure these are not at levels that indicate adverse eutrophication effects. Concerning UWN, the MSFD considers that GES is achieved when 'Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment'. In summary, the MSFD has established criteria and clear environmental thresholds for PCBs (via environmental quality standards (EQS) and the environmental assessment criteria (EAC) of OSPAR), for some PFAS in seawater (via WFD and EQS), and for nutrients (via WFD). Recently, MSFD has proposed thresholds for UWN (anthropogenic impulsive sound and anthropogenic continuous low-frequency sound) (C/2024/2078), while development of thresholds for MP is underway (Table 2).

3.1.1.3 The Zero Pollution Action Plan

Alongside the MSFD objectives, the ZPAP (COM (2021) 400) describes environmental targets with a specific, measurable, and time-bound character for nutrients and MPs (Table 2). The ZPAP sets specific goals to obtain measurable reductions in the losses or releases of MPs and nutrients into the environment (Table 2), although without specifying how the percentage reduction proposed for MPs should be interpreted (e.g., mass based). The ZPAP's source-oriented approach to emission reductions is further reinforced by the REACH regulation. According to the EC, the combined effects of all types of pollution turned out to be of far greater concern to human health and the environment than just looking at an individual substance (SWD (2020) 250; SWD (2021) 141). It must be considered that individual pollutants are not emitted into a pristine environment but become added to the mixture of chemicals (and subsequent effects) that have accumulated over time due to human activities on land and at sea. The EC concludes that there is no thematic overview on pollution that brings all these individual pieces of information together and provides an integrated picture, which is reflected in the lack of indicators for the combined exposure to mixtures of chemicals, and their cumulative effects on human and ecosystem health (SWD (2021) 141). This aligns with the vision of the MSFD, which addresses the cumulative effects of human activities in marine environments, aiming to protect the health of marine ecosystems across Europe. To assess the health of the marine environment, detect human-induced changes in seas and oceans, and identify their causes, several biological effect indicators have been proposed within a framework and methodology designed for integrated use alongside contaminant measurements in biota, sediments, and potentially water (Vethaak et al., 2017). This assessment framework offers a suitable approach for evaluating GES under Descriptor 8 of the European Union (EU) MSFD. Although a good example, EU legislation generally lacks a comprehensive and integrated approach to assessing the combined effects of different chemicals across various legislative domains such as the WFD and MSFD (SWD (2020) 250). To further improve the way chemicals and their mixtures are assessed, the EU incorporates tools like the Mixture Assessment Factor (MAF) and the Multiplying factor (M-factor) (EC/1907/2006, EC/1272/2008, COM (2020) 667).

3.1.1.4 EU responsibilities

In terms of European Union (EU) responsibilities, the Directorate-General for Environment (DG ENV) leads EU environmental policy, overseeing environmental directives such as the Habitat Directive, the WFD and the MSFD. DG ENV is also (co-)responsible for strategies and policies, such as the EU Biodiversity Strategy for 2030, the Soil Strategy, the ZPAP, the EU Green Deal, Environmental Impact Assessment Directive, Environmental Noise Directive, Urban Wastewater Treatment Directive, Priority Substances Directive, Drinking Water Directive, Chemicals Strategy, Stockholm Convention, legislation on Industrial emissions, Regulation on POPs, Nitrates Directive, National Emission Reduction Commitments Directive and Industrial Emissions Directive. The REACH Regulation of the EU falls under the authority of the EU chemical agency ECHA, with DG Internal Market, Industry, Entrepreneurship and SMEs (DG GROW) as ECHA's main partner, alongside DG ENV. The EU Mission "Restore our Oceans and Waters by 2030" is under the responsibility of the DG for Research and Innovation (DG RTD), which is implemented in line with the EU ZPAP. Other directorates such as DG MARE, DG CLIMA, DG ENER, DG MOVE, DG SANTE and DG AGRI are involved for specific sectors or emission sources or effects related to (marine) pollution governance (Devriese et al., 2023). In short, the EU's environmental governance is highly interdependent, with multiple DGs sharing responsibilities across a wide array of policies and strategies, highlighting the complexity and reflecting the interconnectedness of institutional frameworks. This is especially true in the context of (marine) pollution governance, where a source-to-sea approach is essential for effective management and mitigation.

3.1.2 Challenges in assessing the current environmental status of EU waters

For historical pollutants such as PCBs and long-standing pollution by excess nutrients, for example, well-developed monitoring programmes have been in place for many years through frameworks like the MSFD, WFD, or Regional Seas Conventions (Table 3). However, progress evaluations have shown that this still offers no guarantees for achieving GES (COM (2025) 3). Despite being banned, PCBs persist in marine sediments and biota at concentrations that can cause harmful effects on marine life, mainly due to their long half-life and the near impossibility of removing them from fine sediment fractions (European Environment Agency, national contributions). In coastal areas of the European Union (EU), nutrient concentrations in the water often remain problematic, despite years of regulatory and monitoring efforts (European Environment Agency, national contributions). This is attributed to delayed ecosystem responses, regional inconsistencies in monitoring and assessment approaches, and continued nutrient inputs from diffuse sources, primarily from agriculture (Devriese et al., 2023; SWD (2025) 1). As an emerging pollutant, PFAS are classified as priority hazardous substances under the WFD and voluntary compounds under the MSFD, but an adequate and continuous monitoring programme still needs to be established. Regarding UWN, MS initially established operational thresholds aimed at the "avoidance of anthropogenic impulsive sound and acoustic disturbance" (Banfi et al., 2021a, 2021b, 2021c). Research

TABLE 3 Criteria for evaluating the current environmental status based on selected pollutants.

Evaluation criteria	PCBs	Excess nutrients	MPs	PFAS	UWN	Cumulative effects
Monitoring programme in place	+	+	+/-	+/-	+	-
	Yes, MSFD	Yes, MSFD	In development, MSFD (next cycle 2022-2027)	Voluntary compounds under MSFD, monitoring established in WFD	Yes, recently drafted, MSFD, mainly via Regional Seas Conventions	No; Almost no usable information available
Good environmental status	+/-	-	-	-	-	-
	Not fully achieved	Working on consistent levels of ambition, not realised	Not assessed, unknown or not reported	No overall description of the current environmental status, GES not assessed	Working on coherence and regional cooperation	Not assessable
Baseline data	+	+	+/-	-	+/-	-
	Available	Available (DIN and DIP), data on nutrient losses is being collected	No overall quantitative assessments for microplastics levels in marine environments, fragmented data on uptake	Data gap, especially for marine, not covering all PFASs, only few quantitative assessments	Sound maps needed, general lack of data and status assessments	Very scarce information
Source emission knowledge	+	+/-	+/-	+/-	+	
	Well-known, PCB ban in place	The containment of nutrient inputs from diffuse sources is a challenge	Source emissions are known, but quantified assessments are lacking	Although insights on source emissions are available, limited knowledge on transport routes	Characterisation of most of the continuous and impulsive sound sources	Not directly applicable
Understanding risk and harm	+	+/-	-	+/-	-	-
	Known risks	A challenge concerns the delaying effect between the actual nutrient input and the eutrophication effects	No established link between harm and environmental levels yet	No complete picture of environmental risks, gap on ecotoxicity	Knowledge gap on harm and contributions of different sources, recognised as a threat to marine life	Huge knowledge gap, although the importance of understanding cumulative effects is recognised

Score and colour code: + (green): criteria are fully met, well-defined, consistent, and supported by clear, verifiable data. +/- (yellow): criteria are partially met, ambiguously defined, inconsistent, or supported by insufficient or inconclusive data, with any of these conditions sufficient for classification as yellow. - (red): criteria are not available, or multiple deficiencies in the criteria, such as being poorly defined, inconsistent, or unsupported by reliable data, result in an inability to evaluate or make informed conclusions.

efforts across Europe, driven by the MSFD, have encouraged the development of specific monitoring programs and the establishment of threshold values to define GES for UWN (Merchant et al., 2022; C/2024/2078). For MPs, GES is mainly described by the MS as 'not assessed', 'unknown' or 'not reported'. To address this, all MS should cooperate to align and agree on consistent levels of ambition for GES, not only for MPs, but also for UWN, PFAS, and nutrients (Banfi et al., 2021a, 2021b, 2021c; COM (2025) 3).

On top of the previously mentioned challenges, several additional issues must also be addressed to achieve effective marine pollution management. Central to these efforts is the need for solid baseline data, which serves as a foundation for understanding and addressing (marine) pollution. While such data is available for legacy pollutants such as PCBs and nutrients, significant environmental data gaps and a lack of quantitative status assessments remain for UWN, PFAS, MPs, as well as for the cumulative effects of all pollutants (Devriese et al., 2023). Although the sources of pollutants, such as MPs and PFAS, are relatively well-identified, the quantitative assessment of the source emissions and the pollutant transport pathways often remains inadequate for practical application. Diffuse sources present a challenge for nutrients, while for impulsive sound, the monitoring approach including combined effects of multiple sources lacks sufficient clarity and harmonisation (COM (2020) 259; Banfi et al., 2021a, 2021b, 2021c; COM (2025)3). Furthermore, the relationship between environmental concentrations of pollutants in marine waters and their ecological effects is highly complex. For many pollutants, such as MPs, UWN, and PFAS, there is often no established causal link between observed concentrations and demonstrated harmful effects, despite these pollutants being widely recognized as threats to marine life (Devriese et al., 2023). This challenge is further exacerbated by the delayed or cumulative effects frequently observed between exposure and impact, as demonstrated by eutrophication caused by nutrient inputs. When considering the marine environment as a dynamic system exposed to a mixture of pollutants, the potential for synergistic and compounding effects across ecological scales adds another layer of complexity to effective pollution management (Landrigan et al., 2020).

3.2 Evaluation of EU policy targets – Assessing their ambition and practical relevance

When evaluating European policy actions and objectives (based on Supplementary Table 1), the goals and targets are often formulated with specificity and timeframes but are not always expressed quantitatively, which is crucial for ensuring measurability and effectively tracking progress. Among the selected case study pollutants, except for MPs, quantitative environmental targets (threshold levels) for the marine environment have already been defined (PCBs, nutrients), proposed (UWN) or are under review (PFAS) (Table 4). Robust baseline data and monitoring are often lacking, hindering comprehensive environmental assessments and comparisons with targets and thresholds (Tables 3 and 4).While the MSFD includes criteria that aim to link environmental concentrations with effects, such as the secondary criterion D8C2 addressing health of species and the condition of habitats, establishing such causal relationships remains inadequately established for several types of pollution (e.g., MPs, PFAS, UWN). The knowledge gaps regarding transport pathways and the relative contributions of various emission sources continue to complicate baseline assessments and target clarity. This situation may lead to the formulation of targets and goals that are sometimes arbitrary, lacking clarity and definitiveness. Consequently, many policy goals and targets are overly ambitious and unrealistic, and, in some cases, simply unattainable. While certain MSFD thresholds are challenging, such as those for PCBs and nutrients, they remain attainable in principle, provided the right conditions and efforts are in place (Table 4). Other challenges can also complicate the decision-making process, such as the lack of standardised terminology (e.g., microlitter versus microplastic or bioacoustical terminology) (Dozier et al., 2023), preventing environmental assessments (e.g., in the context of GES) from being directly applicable for the evaluation or revision of other European Union (EU) pollution targets.

According to the EC, the ZPAP target for reducing nutrient discharges and emissions is one of the most ambitious measures at combating nutrient pollution (European Commission. Joint Research Centre, 2022): 'by 2030 the EU should reduce by 50% nutrient losses'. However, this study has categorised the target as unfeasible, more specifically as impossible to assess in terms of its attainability (Table 4). This is primarily because it is difficult to quantify diffuse sources, making the target challenging to understand. Moreover, the status and progress towards achieving this target cannot be determined, which limits its attainability. Future efforts must focus on ensuring consistency in environmental threshold levels and target descriptions amongst regions and harmonisation of monitoring methods, also between MSFD and WFD approaches ((Axe et al., 2022; COM (2020) 259).

Based on the currently available data and knowledge, it appears that the EU ZPAP target ('by 2030 the EU should reduce by 30% microplastics released into the environment') for MPs is not attainable (Table 4), primarily due to the data gap concerning microplastic fluxes into the environment. However, the EC states that addressing intentionally added MPs only would be sufficient to meet the total MP inflow reduction target of 30% into the environment (European Commission. Joint Research Centre, 2022). This means the EC assumes that the REACH restriction (focusing solely on intentionally added microplastics in products) will be sufficient to meet the reduction on emissions levels to the environment. However, this cannot currently be verified due to the lack of (environmental) data on the actual relative contribution of intentionally added microplastics to the total flow of microplastics. It should also be noted that the EU ZPAP target on MPs reduction is expressed in percentages, however, no further details are provided to specify whether this refers to volume, mass, or item counts, making it difficult to fully understand the reduction target.

For UWN, the ZPAP refers to the MSFD for a relevant approach and mitigation in the marine environment. Building on expert judgement, the proposed MSFD thresholds are considered meaningful with respect to ecosystem health, but are still difficult to fully grasp due to the current knowledge gaps (Table 4). Scientific evidence points to additional challenges, such as a lack of knowledge or the scale of impact for UWN (COM (2022) 674). The urgency of consolidating efforts, along with the need for harmonised approaches (Kopke et al., 2025), contributes to MSFD thresholds being categorised as unattainable.

In the context of environmental governance, PCBs, nutrients, and PFAS (only in inland surface waters) can serve as exemplary policy practices for addressing other chemical pollutants and environments. This is primarily due to their well-established baselines (for selected chemicals in the case of PFAS), robust scientific insights and the expectation that MS should be able to establish realistic and achievable environmental thresholds for these contaminants. However, meeting those environmental thresholds has proven to be challenging. For MPs and PFAS in marine environments, the EC considers REACH restrictions as a crucial first step to address emission levels to the environment (European Commission. Joint Research Centre, 2022). Such source-based restrictions and their ability to drive significant environmental improvement remain uncertain, particularly due to ambiguities in terms like 'non-essential use' and 'intentionally added,' which could create regulatory loopholes or necessitate assessments based on assumptions. Recently, the EC published a guidance document on the essential use concept for chemicals (C/2024/2894), to increase regulatory efficiency.

Due to the high degree of complexity and the potential cumulative effects, it can take years of targeted research before a real assessment can be made of the risks associated with emerging contaminants on the ecosystem (and humans). In these cases, the application of the precautionary principle should be considered,

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TABLE 4 Feasibility of the EU environmental targets based on benchmarking with the current environmental status.

Pollutant	EU environmental policy	Description of the environmental target		Current environmental status			Feasibility of the target	
		Key target or threshold (Table 2)	Time-bound	Credible data	Measurable	Knowledge	Understandability	Attainability
PCB	MSFD (OSPAR, WFD, EQS)	Sum of 7 indicator PCBs (sediments, fish and other biota), or individual OSPAR EAC values for 7 indicator PCBs	+ Cycle, 2022-2027	+ Available	+ Yes, data is available, target is quantitative	+ Available	+ Yes	+ Yes, but challenging due to historical pollution
Excess nutrients	ZPAP – MSo – FFS - BS	By 2030: -50% nutrient losses.	+ 2030 (baseline 2012-2015)	+/- Data are still being collected	+/- Target is quantitative, data not assessed yet	+/- The containment of nutrient inputs from diffuse sources is a challenge	- Not possible to fully understand	- Impossible to assess
	MSFD (WFD)	Levels cause no adverse eutrophication effects.	+ Cycle, 2022-2027	+ Yes (DIN and DIP)	+ Yes	+/- A challenge concerns the delaying effect between the actual nutrient input and the eutrophication effects	+ Yes	+ Not impossible, but challenging
MP	ZPAP - MO	By 2030: -30% release in environment.	+ 2023 (start: 2015)	+/- No overall quantitative assessments for microplastic fluxes into the environment	+/- Target is quantitative, credible data for assessments is lacking	+/- Source emissions are known, but quantified assessments are lacking	- Not meaningful, fluxes into environment are not quantified	- Impossible to assess
	MSFD	No harm to the environment; no effect on species' health.	+/- Cycle, 2022–2027 if implemented	+/- No overall quantitative assessments for marine environment, fragmentated data for microplastic update and ecosystem effects	- No quantitative target yet	- Knowledge gap on environmental harm	- No established link between harm and levels yet	- Impossible to assess
PFAS	MSFD (WFD, EQS)	Voluntary: concentrations of contaminants do not exceed the threshold values. Threshold under discussion.	+/- Cycle, 2022–2027 once implemented	- Data gap on contamination levels and quantitative assessments	+/- Target is quantitative (via WFD), no credible data	+/- No complete picture of environmental risks, gap on ecotoxicology	- No idea, not understandable for marine environments	- Voluntary compound, impossible to assess, data gap

(Continued)

TABLE 4 Continued

Pollutant	EU environmental policy	Description of the environmental target		Current environmental status			Feasibility of the target	
		Key target or threshold (Table 2)	Time-bound	Credible data	Measurable	Knowledge	Understandability	Attainability
	WFD (EQS)	Inland surface water: annual average of 0.65 ng/l; max. allowable concentration of 36 µg/l.	+	+/-	+	+/-	+	+
			Cycle, 2022-2027	Data in inland surface water not covering entire PFAS group	Target is quantitative, baseline data is available	Limited knowledge of transport routes	Yes	Not impossible, but challenging
		Other surface waters & seawater: annual average of 0.13 ng/l; max. allowable concentration of 7.2 µg/l.	+	-	+/-	+/-	+/-	-
			Cycle, 2022-2027	Data gap for certain parts of environments (especially marine), data not covering entire PFAS group	Target is quantitative, baseline data is not available	Limited knowledge of transport routes and marine levels of PFAS	Not understandable for marine environments	Impossible to assess
UWN	MSFD	Impulsive sounds: no adverse effect on populations of marine animals. Thresholds for short-term and long-term exposure.	+	+/-	+/-	-	+/-	-
			Cycle, 2022-2027	Sound maps needed, general lack of data on underwater noise and status assessments are very scarce for EU waters	Proposed target is quantitative, credible data assessments are scarce	Knowledge gap on environmental harm and contributions of different sources, recognized as a threat to marine life	Meaningful, clear definition of a marine habitat/area needed	Impossible to estimate and to assess
		Continuous low-frequency sounds: no adverse effect on populations of marine animals. Threshold available.	+	+/-	+/-	-	+/-	-
			Cycle, 2022-2027	Sound maps needed, general lack of data on underwater noise and status assessments are very scarce for EU waters	Proposed target is quantitative, credible data assessments are scarce	Knowledge gap on environmental harm, widely recognized as a threat to marine life	Not possible to fully understand, clear definition of a marine habitat/area needed	Impossible to estimate and to assess

Score and colour code: + (green): criteria or targets are fully in place, well-defined, consistent, and supported by reliable, accessible data. +/- (yellow): criteria or targets are partially defined, fragmented, not fully understood, or challenging to assess due to incomplete or inconclusive data, with any of these conditions sufficient for classification as yellow. - (red): multiple deficiencies, such as being absent, undefined, or unsupported by reliable data, result in an inability to evaluate or make informed conclusions.

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particularly given the long-term effects (e.g., PFAS), the inability to remove pollutants from the environment, and the anticipated rise in environmental levels of certain (chemical) contaminants in the near future (e.g., MPs). This is especially relevant when there is evidence suggesting that these contaminants pose a plausible risk.

3.3 Stepping stones towards ambitious yet feasible EU environmental policy goals for marine pollution

As outlined in the preceding discourse, the governance landscape for addressing marine pollution is fragmented, with notable gaps in pollutant coverage and the allocation of institutional responsibilities (Dauvergne, 2018; Zulfiqar and Butt, 2021). The latter are shaped by factors such as the stages of pollution, from source inputs (causes) to environmental outcomes (results), and by spatial demarcations in regulation (land versus sea or inland waters versus seawater). These issues are further exacerbated by data deficiencies, hampering knowledge development and causing uncertainties. The limitations or challenges outlined above can serve as a basis to define recommendations, so-called stepping stones that aim to enhance the strength and effectiveness of (future) policy measures on marine pollution and can be used to evaluate the impact and effectiveness of existing policies. Five stepping stones have been identified, with the important note that they do not stand alone but interact with one another (Figure 1; Table 5). Importantly, these stepping stones are reinforced by recent evaluation findings from European Commission reports (e.g., SWD(2025) 1; SWD (2025) 52), particularly regarding policy efficiency and effectiveness, stakeholder participation, and legislative coherence and alignment. The alignment between the independently developed stepping stones and recent policy evaluations highlights the robustness and relevance of the findings, indicating convergence across diverse approaches.

3.4 Integrating marine pollution within EU policy frameworks: enforcement, compliance, and broader environmental quality

Adopting an integrated perspective on marine pollution can facilitate a deeper understanding of key emission sources and distribution dynamics, assess impacts on the marine environment, monitor and evaluate policy effectiveness, and ultimately guide the development and implementation of more targeted and effective

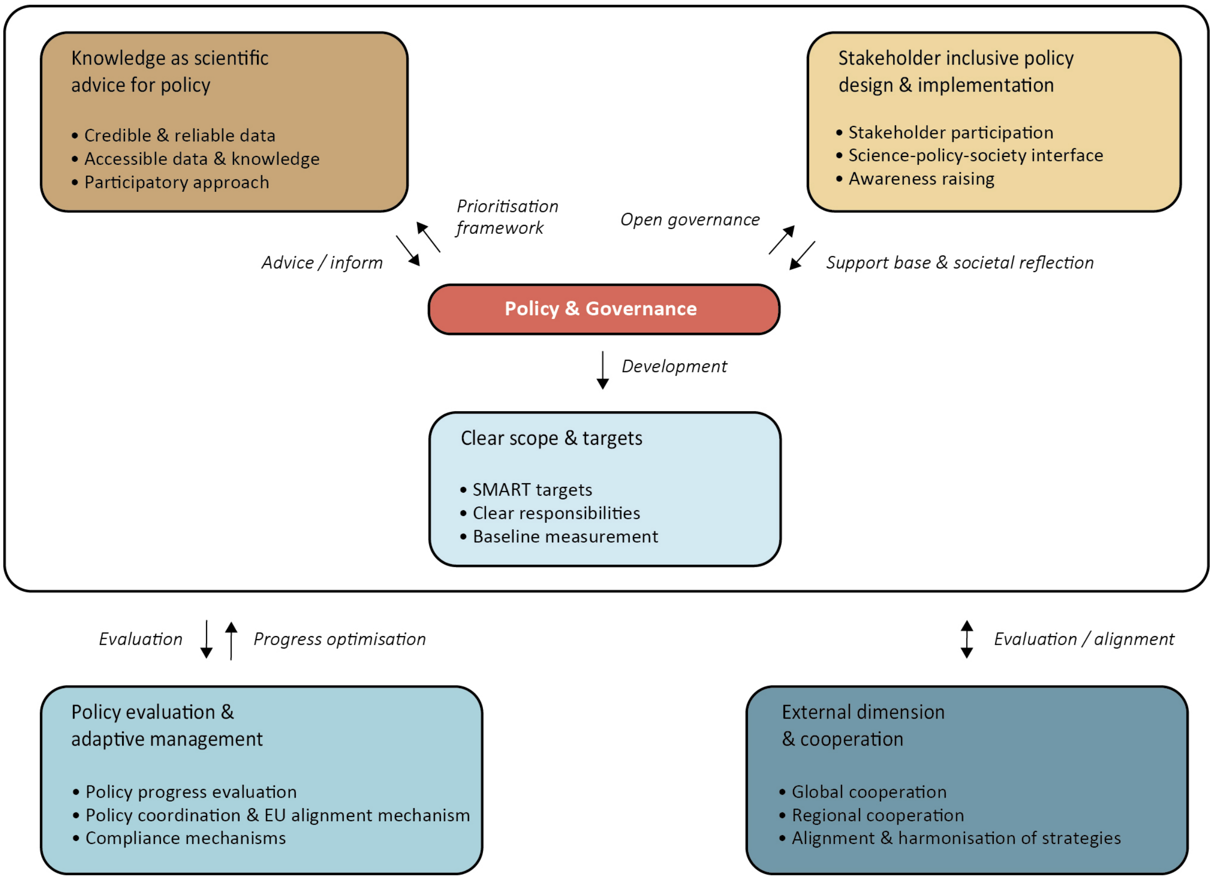

FIGURE 1
Stepping stones and building blocks to advance EU policy of marine pollution. (adapted from Devriese et al., 2023)

TABLE 5 Stepping stones and building blocks to advance EU policy of marine pollution.

Stepping stones	Building blocks	Explanation
Knowledge as scientific advice for policy	Credible & reliable data Accessible data & knowledge Participatory approach	'Knowledge as scientific advice for policy' highlights the necessity of credible and reliable environmental and source emission data for effective environmental assessments. It calls for standardised methods to ensure data quality and emphasises the importance of accessible data through EU and regional databases for coherent information flow to stakeholders (FAIR-data). A participatory approach is advocated, encouraging interdisciplinary collaboration among researchers and regions to better understand environmental processes and risks, thereby enhancing policy outcomes in marine protection towards societal goals.
Stakeholder inclusive policy design and implementation	Stakeholder participation Science – policy - society interface Awareness raising	Although not elaborated on in this publication, the importance of 'Stakeholder inclusive policy design and implementation' cannot be overstated. Stakeholder participation in policymaking, focusing on transparency, accessibility, and responsiveness is essential to policy design and implementation (Devriese et al., 2023). It promotes initiatives that bridge the science-policy-society interface, ensuring that policymakers have access to the latest research results. Additionally, it emphasises the need for awareness-raising efforts to inform stakeholders and foster collaboration. From the EC's perspective, there is a strong emphasis on raising awareness and engaging European businesses, civil society, the research community, and other stakeholders, as demonstrated through the Zero Pollution Stakeholder Conference and Platform.
Clear scope and targets	SMART targets Clear responsibilities Baseline measurement	'Clear scope and targets' emphasises the establishment of SMART targets which are scientifically grounded, understandable, measurable and clearly defined in relation to specific pollutants and their emission sources (e.g., human activities). It highlights the importance of assigning clear responsibilities to actors for effective governance and follow-up, ensuring accountability in policy implementation. Furthermore, it stresses the need for baseline monitoring data (see Knowledge as Scientific Advice for Policy), which is essential for continuous assessments, evaluating progress toward achieving targets, and refining those targets to make them both attainable and comprehensible.
Policy evaluation and adaptive management	Policy progress evaluation Policy coordination and EU alignment mechanisms Compliance mechanisms	Effective pollution governance must prioritise the continuous evaluation of policy progress towards targets, advocating for interim monitoring through comprehensive frameworks that assess feasibility and ensure compliance. It must also address uncertainties, such as the presence of emerging contaminants, their potential ecological impacts, and the cumulative effects of multiple stressors on marine ecosystems. 'Policy evaluation and adaptive management' emphasise the importance of a coordinated policy mechanism that aligns EU environmental targets with broader strategies, such as the ZPAP ambition (Devriese et al., 2023). Such coordination ensures a unified approach across jurisdictions, facilitating more effective implementation and coherence of policies. Besides, these mechanisms should include modules to identify emerging threats, assess their long-term (health) effects, and incorporate new knowledge into decision-making processes. This approach will enable proactive responses to unforeseen challenges and ensure that marine pollution management remains resilient and responsive to new scientific evidence and changing environmental conditions.
External dimension and global cooperation	Global cooperation Regional cooperation Alignment and harmonisation of strategies	Lastly, 'External dimension and global cooperation' advocates for embedding EU ambitions within a global context (e.g. UN Decade of Ocean Science or the UN Sustainable Development Goals), engaging in cooperative efforts with third countries and international organisations to address pollution's root causes (Devriese et al., 2023). It promotes regional cooperation to optimise and standardise environmental assessments and data sharing, ensuring harmonisation and alignment of strategies. Additionally, it emphasises the EU's role in global environmental agreements and processes, addressing emerging challenges like marine plastic pollution through collaborative and transdisciplinary initiatives.

The colours refer to the respective stepping stones shown in Figure 1.

management strategies. Achieving this, however, requires a robust governance framework capable of understanding and deconstructing the complexity of marine pollution, identifying strategic entry points for intervention, and enabling targeted policies that balance societal and environmental objectives. The value of integrating a systems perspective, connecting sources and drivers to dynamics and distribution to impacts and management responses has been proposed for marine litter by Hardesty and Wilcox (2017).

Pollution is intrinsically connected to marine environmental quality, and an assessment of European Union (EU) nature conservation and spatial planning instruments highlights varying degrees of pollution mitigation integration (Table 6), each accompanied by unique challenges and implications. The WFD and MSFD share principles like integration, ecosystem-based approaches, and public participation, aligning with broader EU frameworks such as the Habitats Directive (O'Hagan, 2010). Despite these shared goals, they use different methodologies to assess aquatic environments, treating river basins and marine regions as separate systems instead of interconnected ones (Bigagli, 2015; Black et al., 2019a, 2019; Borja et al., 2010), where the MSFD oversees only those coastal elements that are not covered by the WFD (Bigagli, 2015). While the WFD focuses on strict conservation goals aligned with the Habitats Directive, the MSFD lacks similar mechanisms, leaving MS responsible for addressing overlaps (Black et al., 2019b; Borja et al., 2010; O'Hagan, 2010; O'Mahony et al., 2014). Besides EU instruments like the MSFD and WFD, which are specifically designed to address pollution, other EU

TABLE 6 Integration of pollution aspect in EU nature conservation and spatial planning.

EU instrument	Pollution consideration and integration	Levels of reference to pollution
EU Biodiversity Strategy (COM (2020) 380)	Mentions pollution and links it to several other EU strategies, including the ZPAP, the Chemicals Strategy for Sustainability, and the Integrated Nutrient Management Action Plan. This strategy is part of the EU Green Deal.	High – directly refers to pollution and aligns with multiple EU strategies.
Commission Staff Working Document 'Criteria and Guidance for Protected Areas Designations' (SWD (2022) 23)	Recognizes urban and peri-urban protected areas' role in mitigating pollution and aligns with directives like the Natura 2000, WFD, and MSFD, but does not go into significant detail on the specific aspects of pollution.	Moderate – Mentions pollution but only superficially. While the document refers to relevant EU legislation, it does not focus on pollution.
Habitats Directive (92/43/EEC)	Does not directly address pollution or related policies.	Low – no direct reference to pollution.
Birds Directive (2009/147/EC)	It emphasizes the importance of preventing pollution and disturbances that affect birds and their habitats but does not set specific targets or criteria. Additionally, there is no direct integration of this objective into other EU legislation.	Moderate – The focus is on habitat protection, and the importance of pollution is acknowledged. However, no further practical references or guidance are provided.
Maritime Spatial Planning Directive (2014/89/EU)	Briefly acknowledges the contribution of MSP to the goals of the WFD and MSFD, indirectly addressing pollution without specific mention.	Low – indirect reference to pollution through alignment with WFD and MSFD.
Regulation (EU) 2024/1991 on Nature Restoration	Includes pollution reduction and elimination as part of nature restoration, and links it to several other EU directives addressing environmental pollution management.	High – Clear mention of pollution, with a focus on nature restoration and ecosystem health. Indirect implications for pollution reduction are included through references to EU legislation.

instruments (Table 6) either indirectly reference EU strategies or legislation aimed at tackling pollution or mention it without directly addressing the issue. These variations highlight the diverse approaches to environmental management within the EU framework.

In addition to evaluating whether the individual targets and thresholds for marine pollution are achievable, it is also important to consider the broader framework of ambitions and objectives for the sea, marine areas and transition zones. Are the thematic objectives compatible with the goals for marine pollution, or do conflicts or challenges arise that could jeopardise their feasibility? Ultimately, all aquatic and marine frameworks should be interconnected and refer to the existing WFD and MSFD goals or build on their outcomes. This scenario would create a more cohesive and holistic enforcement strategy, ensuring that MS adhere to the overarching goals of marine protection and sustainable practices. However, the ambitious goals set by these directives may be too difficult for some MS to achieve. Therefore, while clarifying legal requirements across different frameworks will be key to making meaningful progress in protecting the marine environment, achieving these goals is likely to depend on enabling conditions, such as increased support from EU.

In the context of marine environmental protection, the policy strategy should remain ambitious — pushing for higher goals that drive more substantial improvements. However, there is a risk that such goals and targets are overambitious, and it is uncertain what the consequences might be. A crucial distinction in understanding compliance lies in differentiating between binding legislation, such as EU regulations and directives, and the non-binding policy documents that serve as guidance. This distinction is crucial, as MS can face legal action for failing to meet binding targets, but there are no legal repercussions for non-compliance with policy documents. When it comes to compliance and enforcement, the legal framework is often unclear, particularly regarding how GES is defined. For example, an MS might fail to meet Good Ecological Status under the WFD, but still pass the GES under the MSFD, or vice versa, depending on how GES is interpreted—whether focusing on ecological, chemical, or environmental status. Furthermore, spatial issues, such as defining estuaries, transnational waters, and protected areas, create further complications in aligning legal obligations in a source-to-sea or marine context. These overlapping frameworks sometimes result in contradictory requirements or targets, making enforcement challenging.

4 The way forward - enhancing European pollution policies

Improving European policy related to pollution requires a comprehensive, multi-dimensional approach that strengthens regulatory frameworks (including the effective enforcement of existing directives, such as the Air Quality Directive, WFD, and Waste Framework Directive, across all MS), integrates scientific research, encourages cross-sectoral collaboration, and raises public awareness (Maes et al., 2023a). Effective enforcement can be achieved by addressing compliance gaps through infringement procedures and regular assessments. Furthermore, it is essential to set ambitious and feasible pollution reduction targets at European Union (EU) or regional level, with particular emphasis on aligning with similarly ambitious international agreements, such as the Paris Agreement, and to ensure robust monitoring and reporting mechanisms are in place (Maes et al., 2023a). Pollutant-specific legislation is another avenue for improvement. The EU should introduce stricter controls on the most harmful pollutants, such as heavy metals, toxic chemicals, and carbon emissions, and focus on emerging concerns, including MPs (Gago et al., 2022). The application of the precautionary and polluter pays principles should be reinforced, stopping pollution before it leaks in the environment and making industries more accountable for their environmental impact by introducing financial penalties and rewards that incentivise pollution reduction and green technology innovation.

A major focus of policy improvement should also be on promoting a circular economy and waste reduction. Transitioning from a linear to a circular economy model is crucial for reducing waste, encouraging recycling, reuse, and extending the lifecycle of products, but can also have significant impact in reducing pollution. Policies such as extended producer responsibility (EPR) schemes, higher recycling targets, and the reduction of single-use plastics will be pivotal. Strengthening plastic pollution policies, expanding support for alternative materials, and implementing robust waste management strategies while holding industries accountable for waste disposal are essential steps in reducing plastic waste and minimising marine pollution. Implementing zero-waste policies at municipal and regional levels will further reduce waste, incentivising local governments to develop comprehensive waste management strategies focused on minimising landfill use and enhancing recycling (Maes and Preston-Whyte, 2023).

Furthermore, the need for integration of pollution policies with other pollution-related aspects, such as human health, is an important step for policy improvement. By explicitly incorporating health considerations into environmental policy-making, the EU can better address the direct link between pollution and human health. A healthy environment and human well-being are intrinsically connected, with improvements in environmental quality directly contributing to enhanced public health outcomes, while efforts to safeguard human health often drive stronger environmental protections, creating a mutually reinforcing cycle of benefits. This is particularly important for reducing pollution hotspots that adversely affect vulnerable populations, such as children, the elderly, and those with pre-existing health conditions. Furthermore, environmental justice should be prioritised, ensuring that marginalised communities, such as low-income neighbourhoods or areas with high industrial activity, are not disproportionately exposed to pollution e.g., the toxic PFAS triangle Beveren, Zwijndrecht and Antwerp polluted by 3M in Belgium (GRID-Arendal, 2023).

In tandem with these efforts, boosting innovation and green technologies is essential. EU funding for green innovation should be increased, particularly for pollution control technologies, new materials, and sustainable practices across agriculture, industry, and transport sectors. Promoting clean energy and low-emission and quieter transport will also contribute to decarbonising the economy and reducing pollution. Strengthening policies aimed at decarbonising transport in urban areas, incentivising public transport, and supporting the transition to renewable energy sources will also be key components of this strategy (GRID-Arendal, 2024). Similarly, implementation of policies such as the EU's Safer and Sustainable by Design (SSbD) framework, which is currently in advanced stages of development, has strong potential to facilitate the replacement of high-risk chemicals and materials in consumer products, as well as ensuring new chemicals and materials developed in the future will have low impacts if released to the environment (Caldeira et al., 2022; C/2022/8854).

Enhancing collaboration and stakeholder engagement is another crucial step toward improving pollution policies. Public-private partnerships can drive innovation and best practices in pollution control, while cross-border cooperation is essential for tackling transboundary pollution, such as air or noise pollution and marine litter. Encouraging community and youth involvement in pollution monitoring and awareness-raising campaigns will also empower citizens and foster a sense of environmental responsibility that will be taken forward as core values into future generations. Effective pollution-related policies must integrate socio-economic considerations, ensuring that regulatory measures not only mitigate environmental harm but also account for economic viability, social equity, and the diverse needs of affected communities to achieve sustainable and inclusive outcomes.

The role of environmental NGOs and civil society must also be strengthened. Empowering NGOs to participate in decision-making processes and advocating for stronger pollution controls is vital (Cowan et al., 2024). They can contribute to pushing for stronger enforcement and binding targets to protect EU seas (Seas at Risk, 2025). Likewise, civil society should actively participate in policymaking to ensure transparency, accountability, and public participation (Hartley et al., 2018). Improving data collection and transparency is critical for effective policy development (Maes et al., 2023b). Investing in real-time pollution monitoring technologies, such as satellite systems, Internet of Things sensors, and artificial intelligence -powered data analysis, has the potential to be more cost effective and to provide more precise and continuous information to guide policy decisions (Sandra et al., 2023). Additionally, ensuring public access to pollution data will foster transparency and allow stakeholders to make informed decisions.

To effectively improve European policies on pollution, it is crucial to integrate strong regulatory frameworks, encourage collaboration across sectors, and implement sustainable, forward-thinking strategies. A combination of legal measures, technological advancements, public engagement, and international cooperation will help to ensure that Europe meets its environmental goals while safeguarding public health and ecosystems for future generations. As a region with some of the most advanced policies and frameworks related to pollution, the EU should continue to strengthen its leadership on this global challenge by enhancing its role in global environmental governance and collaborating more closely and effectively with international organisations, such as the United Nations Environment Programme (UNEP) to help develop and establish ambitious global pollution reduction targets and enforce global treaties. In parallel, the EU should build on its regional expertise to reduce environmental pressures more effectively (e.g., COM (2025) 3) and share best practices with other parts of the world. Its regulatory and scientific experience can play a key role in supporting progress toward the Sustainable Development Goals (SDGs), especially in regions where environmental frameworks are still emerging.In this regard, the EU has strategically aligned its regulatory and research frameworks with the objectives of the UN Decade of Ocean Science for

Sustainable Development (2021–2030), aiming to advance clean, healthy, resilient, productive, predicted, safe, accessible, and inspiring oceans, with a particular focus on generating actionable knowledge and fostering international cooperation to combat marine pollution. Core EU policies such as the MSFD, the Common Fisheries Policy (CFP), and the Biodiversity Strategy 2030 directly support the Decade's goals by promoting GES, sustainable fisheries, and the protection of marine ecosystems. Additionally, the EU's investment in large-scale initiatives, such as Horizon Europe, the Copernicus Marine Service, and the European Marine Observation and Data Network (EMODnet), facilitates ocean monitoring, modelling, and data accessibility, thus contributing to a predicted and accessible ocean. The EU Mission "Restore Our Ocean and Waters" further operationalises the Decade's ambitions by fostering regional action on pollution reduction, ecosystem restoration, and sustainable blue economy development. These efforts are underpinned by the European Green Deal and the Circular Economy Action Plan, which address root causes of marine degradation such as pollution and resource inefficiency. Through this integrated approach, the EU not only contributes to the global implementation of the UN Ocean Decade but also enhances scientific cooperation, stakeholder engagement, and policy coherence across scales.

These experiences in marine governance, pollution reduction, and environmental protection provide adaptable models for regions with less developed environmental legislation, including the EU's Regional Seas Conventions and outermost regions. By leveraging established frameworks such as the MSFD, Maritime Spatial Planning, and integrated coastal management, these regions can tailor the models to their own socio-economic and ecological contexts. Fostering collaborative mechanisms with the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) Commission, the Helsinki Commission (HELCOM), the Black Sea Commission and the United Nations Environment Programme/Mediterranean Action Plan (UNEP/MAP), engages countries in mutual learning and helps to further align efforts to address shared environmental challenges, extending beyond EU borders. Moreover, regional cooperation is a key component of the MSFD, as outlined in Article 5(2). This provision mandates that MS sharing a marine region or subregion cooperate to ensure coherent and coordinated measures to achieve the Directive's objectives, particularly with regard to initial assessments, the determination of GES, the setting of environmental targets, monitoring programmes, and the implementation of measures. Strengthening these regional efforts will enhance environmental governance in these regions and support more effective collective action across marine regions. Capacity-building, technical assistance, and the transfer of knowledge through EU-supported initiatives, such as EMODnet, Horizon Europe, and the Mission "Restore Our Ocean and Waters", can further support the implementation of tailored strategies.

The analytical framework presented in this study exemplifies such transferable knowledge, offering practical tools for countries with developing environmental legislation to strengthen regulatory capacity, monitoring, and enforcement. Importantly, aligning regional actions with broader EU and global goals ensures coherence and maximises the impact of conservation and sustainable development efforts.

Author contributions

LID: Conceptualization, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing. TVJ: Data curation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. TV: Methodology, Supervision, Writing – original draft, Writing – review & editing. TM: Methodology, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition. BB: Methodology, Writing – review & editing. LD: Writing – review & editing. AB: Funding acquisition, Writing – review & editing. KK: Funding acquisition, Methodology, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

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

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The author(s) declare that no Generative AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2025.1586918/full#supplementary-material

SUPPLEMENTARY TABLE 1
Longlist of European legislation and policy documents with indicated relevance for the selected pollutants. This table includes only legislation and policy documents that contain relevant references to the selected pollutants (as described in Table 1). As a result, several regulations that may initially appear relevant (e.g., the Environmental Noise Directive) have been screened but are not included. Relevant legislation that solely amends an existing legislative document is not listed separately.

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