



Funded by the European Union's Horizon Europe programme under grant agreement No.101060213.



SOS-ZEROPOL2030

D5.4 Practical Guidance towards zero pollution in our seas for different types of pollutants

Public

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Document Information

Version	Date	Description			
		Responsible	Authors	Reviewed by	Approved by
1	01/7/2026	MIO-ECSDE	MIO-ECSDE		
2	24/7/2026	MIO-ECSDE	VLIZ, UCC, Research Institute for Sustainability (RIFS) at GFZ	MIO-ECSDE	
3	31/7/2026	MIO-ECSDE		MIO-ECSDE	
4	03/8/2026	MIO-ECSDE			UCC

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Suggested Citation:

Vlachogianni, T., Devriese, L., Kopke, K., Del Savio, L., Boteler, B. (2026). SOS-ZEROPOL2030: Deliverable D5.4 Practical Guidance towards zero pollution in our seas for different types of pollutants, 31 pp.

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Please note that the following report is under review and awaiting approval by the SOS-ZEROPOL2030 Project Officer on behalf of the European Commission.

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Executive Summary

Key messages

- Integrated source-to-sea approaches are essential for achieving the European Green Deal's zero pollution ambition.
- Common governance approaches underpin effective zero pollution action, such as prevention at source, integrated source-to-sea governance, policy coherence adaptive governance, science-based decision-making, meaningful stakeholder engagement.
- Pollutant-specific pathways are needed to complement transferable guidance.
- Stakeholder engagement and co-design strengthen zero pollution implementation.
- Strengthening implementation is key to delivering the EU Zero Pollution ambition.

Achieving the European Union's Zero Pollution ambition requires approaches that address the complexity of pollution sources, pathways and impacts across interconnected terrestrial, freshwater and marine systems. While individual pollutants differ in their characteristics, environmental behaviour and governance needs, many of the challenges associated with preventing and reducing marine pollution are shared. This deliverable (D5.4) translates the scientific, governance and stakeholder knowledge generated throughout the SOS-ZEROPOL2030 project into practical guidance that supports the implementation of effective zero pollution approaches in European seas.

The guidance adopts a source-to-sea perspective, recognising that many pressures affecting marine ecosystems originate from activities occurring outside the marine environment and therefore require coordinated action across environmental compartments, sectors and governance levels. Rather than developing new scientific evidence, D5.4 synthesises the project's key findings into transferable governance guidance while identifying where pollutant-specific implementation pathways remain necessary.

The analyses undertaken within SOS-ZEROPOL2030 indicate that future progress towards marine zero pollution depends less on identifying new environmental objectives than on strengthening the coordinated implementation of existing policy ambitions across the source-to-sea continuum.

This guidance was developed through the integration of multiple complementary evidence streams generated within SOS-ZEROPOL2030, including the assessment of the EU Zero Pollution Ambition and governance landscape, stakeholder surveys, Regional Seas Living Labs, the Zero Pollution Parliament, pollutant-specific guidance for per- and polyfluoroalkyl substances (PFAS) and tyre wear particles (TWPs), and the SOS-ZEROPOL2030 Strategic Framework and Roadmap. Together, these activities provide a robust evidence base for identifying common governance principles, implementation needs and future pathways towards marine zero pollution.

The synthesis demonstrates that, despite substantial differences between pollutant groups, effective policy implementation consistently depends on a number of common governance conditions. These include stronger cooperation across sectors and governance levels, prevention through source control and lifecycle approaches, improved monitoring and knowledge integration, effective science-policy interfaces, meaningful stakeholder engagement, adaptive governance and coherent implementation across policy frameworks. These cross-cutting principles form the basis of the transferable guidance presented in this deliverable and the practical recommendations applicable across a wide range of marine pollution challenges.

At the same time, the analysis conducted in SOS-ZEROPOL2030 highlights that transferable governance principles must be complemented by pollutant-specific implementation pathways. Persistent chemical contaminants require precautionary regulation, substitution and management of legacy contamination; nutrient pollution requires integrated catchment-to-coast management and balanced nutrient cycles; microplastics require lifecycle interventions addressing diverse diffuse emission sources; and underwater noise requires spatial, operational and source-control measures supported by harmonised monitoring and maritime planning. Together, these pathways demonstrate how common governance principles can be translated into tailored actions reflecting the characteristics of different pollutant groups.

Overall, D5.4 provides an integrated framework for strengthening marine zero pollution governance by linking transferable governance principles with pollutant-specific implementation requirements. The guidance supports policymakers, competent authorities, Regional Sea Conventions, industry actors, researchers, infrastructure providers and civil society organisations in designing and implementing coordinated zero pollution actions across the source-to-sea continuum. By bridging strategic ambitions with practical implementation, it contributes to the delivery of the European Green Deal, the EU Zero Pollution Action Plan and the broader objective of achieving cleaner, healthier and more resilient European seas.

1. Introduction

1.1. Purpose, Scope & Objectives

The Horizon Europe SOS-ZEROPOL2030 project aims to deliver a stakeholder-led European Seas zero-pollution framework to help achieve the European Union's long-term ambition of zero pollution in European seas (<https://soszeropol2030.eu>). The European Green Deal and the EU Zero Pollution Action Plan establish an ambitious policy agenda to prevent and reduce pollution across environmental compartments (air, water, soil, sediments, biota) while protecting human health and ecosystems. Achieving these policy objectives requires coordinated action across the source-to-sea continuum through the application of the source-to-sea approach (Box 1-1), which recognises the complexity of pollutant sources, pathways, characteristics and effects, and supports coordinated action across land, freshwater and marine systems.

Box 1-1. The source-to-sea approach.

The source-to-sea approach is a comprehensive management strategy that addresses pollution across interconnected terrestrial, freshwater and marine systems. Recognising the interlinkages and dependencies among these ecosystems, it promotes coordinated action across upstream and downstream pathways to ensure that interventions in one part of the system do not inadvertently create impacts elsewhere (Granit et al., 2017; Mathews and Stretz, 2019; Del Savio et al., 2026). Implementing the source-to-sea approach requires integrated governance across sectors and administrative levels, robust monitoring throughout the source-to-sea continuum, coherent policy frameworks, active stakeholder engagement, and adaptive management capable of responding to new evidence and changing environmental conditions (Granit et al., 2017; Mathews and Stretz, 2019; Del Savio et al., 2026).

This guidance translates the scientific, technical and governance findings, together with stakeholder knowledge generated by the SOS-ZEROPOL2030 project into practical recommendations for advancing the EU's zero pollution ambition in European seas. It synthesises evidence across the project's four pollutant groups -nutrients, hazardous substances, microplastics and underwater noise- while drawing on the in-depth guidance developed for the case-study pollutants per- and polyfluoroalkyl substances (PFAS) and tyre wear particles (TWPs). By identifying transferable governance principles alongside pollutant-specific requirements, this document provides policy-relevant guidance to support the design and implementation of effective zero pollution approaches across the source-to-sea continuum.

Specifically, this guidance aims to:

- Synthesise the key scientific, governance and stakeholder insights generated throughout the SOS-ZEROPOL2030 project into practical guidance for preventing, reducing and mitigating marine pollution.
- Identify transferable approaches, good practices and enabling conditions that can be applied across different pollutant groups, while highlighting where pollutant-specific strategies are required.
- Provide practical recommendations for policymakers and other stakeholders to strengthen the implementation of zero pollution measures at European, national and regional levels.
- Incorporate the future pathways and implementation scenarios developed within the project to support strategic planning and evidence-based decision-making towards the EU's zero pollution objectives.
- Promote coordinated action among all relevant actors to accelerate the transition towards cleaner and healthier European seas.

1.2. Target audience

This guidance is intended for a broad range of stakeholders involved in preventing, reducing and mitigating marine pollution and supporting the implementation of the EU Zero Pollution Action Plan across the source-to-sea continuum, including:

- **Policymakers and regulators** – at European, national, regional and local levels, including those involved in the implementation of EU environmental legislation and Regional Sea Conventions, responsible for developing, coordinating and enforcing policies and measures addressing pollution from sources to marine environments.
- **Competent authorities, environmental agencies and river basin authorities** – responsible for environmental monitoring, assessment, permitting, compliance, and the implementation of pollution reduction measures under relevant policy frameworks, including the Marine Strategy Framework Directive, Water Framework Directive and other sectoral legislation. River basin authorities play a particularly important role in addressing upstream sources and pathways of pollution affecting coastal and marine waters.
- **Industry actors and economic sectors** – including manufacturing, chemical production, transport and maritime sectors, agriculture, fisheries, aquaculture, wastewater and waste management operators, and other sectors whose activities contribute to pollutant pressures or whose practices can enable pollution prevention, reduction and mitigation.
- **Researchers and the scientific community** – providing evidence on pollutant sources, emission pathways, environmental fate, impacts, monitoring approaches, and the effectiveness of prevention and mitigation measures to support science-based policy development and implementation.

- **Infrastructure and service providers** – including drinking water and wastewater utilities, waste management operators, port authorities, remediation providers, and other organisations responsible for implementing technical solutions, monitoring environmental pressures, and reducing pollutant releases.
- **Regional organisations, NGOs and civil society organisations** – supporting integrated governance through stakeholder engagement, awareness raising, knowledge exchange, capacity building and the promotion of transparent and participatory approaches towards achieving zero pollution in European seas.

1.3. Methodology

This guidance is based on the integration of scientific evidence, policy and governance analyses, expert knowledge, stakeholder perspectives, and co-design processes generated throughout the SOS-ZEROPOL2030 project. Rather than producing new analyses, D5.4 synthesises and translates the project's findings into practical guidance for advancing zero pollution approaches in European seas.

The methodology adopts a cross-pollutant synthesis approach, integrating evidence from all project activities to identify both transferable governance principles and pollutant-specific considerations. The guidance draws on the EU Zero Pollution Ambition assessment (Devriese et al., 2023) and governance analysis (Van Leeuwen et al., 2023), which together provide the policy and regulatory context for marine pollution management and identify key governance considerations for addressing priority pollutants. It further incorporates stakeholder perspectives on risks, solutions and policy measures obtained through the stakeholder surveys (Vaupotič et al., 2024), as well as insights from the project's Living Labs and knowledge co-creation activities (Van Hulst et al., 2024; Van Hulst et al., 2025; Kopke et al., 2026), which identified implementation needs, governance barriers, opportunities and potential solutions for reducing marine pollution.

The synthesis is further informed by the pollutant-specific guidance developed for tyre wear particles and PFAS (Vlachogianni et al., 2026a; Vlachogianni et al., 2026b), providing examples of how zero pollution approaches can be tailored to different pollutant types. In addition, D5.4 builds on the SOS-ZEROPOL2030 Framework (Boteler et al., 2026) and Roadmap (Vlachogianni et al., 2026), which provide the strategic foundation and implementation pathways for translating zero pollution ambitions into concrete actions and measures for European seas.

Through the integration of these complementary knowledge sources, D5.4 identifies common principles and transferable approaches applicable across pollutant groups, while highlighting where pollutant-specific requirements and targeted interventions are necessary. The resulting guidance supports policymakers, competent authorities, industry actors, researchers and other stakeholders by outlining strategic priorities, future pathways and key enabling conditions for strengthening zero pollution approaches across the source-to-sea continuum.

METHODOLOGICAL APPROACH UNDERPINNING THE SOS-ZEROPOL2030 GUIDANCE

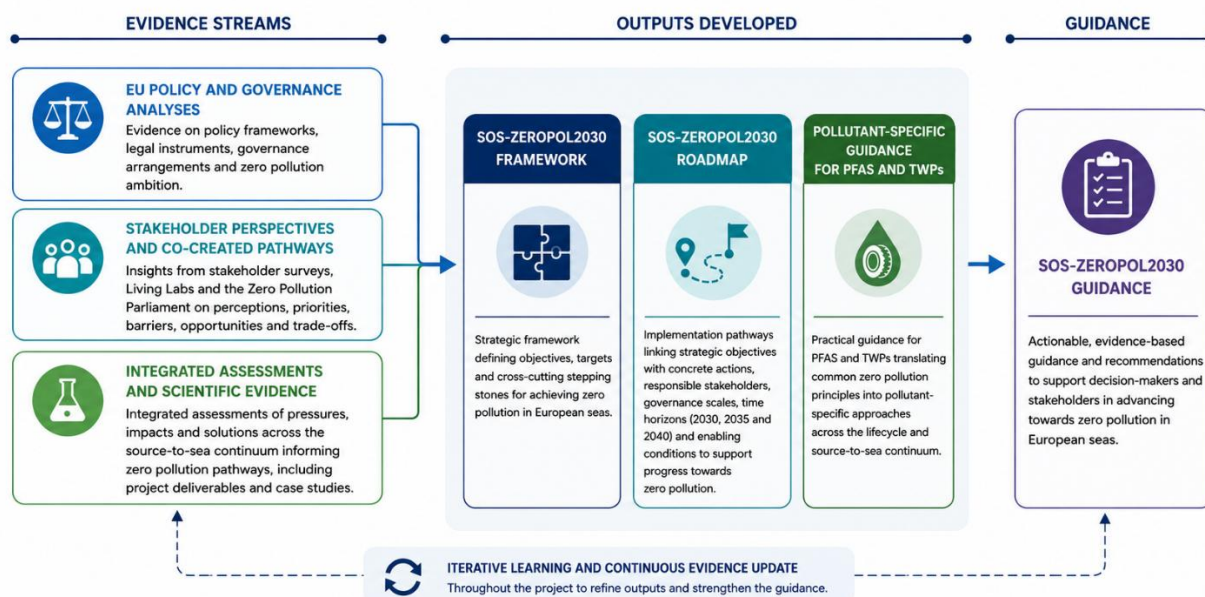


Figure 1-1. Methodological approach underpinning the SOS-ZEROPOL2030 guidance.

2. Knowledge and Policy Foundations

2.1. EU Zero Pollution Ambition and policy framework

The EU Zero Pollution Ambition assessment (Devriese et al., 2023; 2025) provides the overarching policy and governance context underpinning this guidance. It demonstrates that achieving the objectives of the European Green Deal and the EU Zero Pollution Action Plan requires integrated approaches that address pollution across environmental compartments and throughout the source-to-sea continuum.

Marine pollution represents a complex governance challenge due to the diversity of emission sources, the involvement of multiple human activities and the variety of pathways through which pollutants reach marine environments. Its transboundary nature requires coordinated action across governance levels and jurisdictions, as pollutants can travel beyond their original emission sources through rivers, atmospheric transport and marine circulation processes. The EU policy framework therefore increasingly emphasises prevention, reduction and remediation through approaches that address pollution sources, pathways and impacts in an integrated manner.

The assessment provides an overview of the key EU policies and legislative instruments contributing to marine pollution management, including the Marine Strategy Framework Directive (MSFD), Water Framework Directive (WFD), Waste Framework Directive and REACH Regulation, to name a few. Together, these frameworks address pollution from complementary perspectives, including environmental quality objectives, source reduction, chemical regulation, waste management and monitoring requirements.

However, policy responses differ considerably between pollutant groups due to differences in pollutant characteristics, emission pathways, scientific understanding and governance maturity. PFAS management, for example, is strongly linked to chemical regulation and source control under REACH, while microplastics and TWPs require lifecycle-based approaches addressing production, use and end-of-life pathways. Nutrients are primarily addressed through integrated water and marine management frameworks, whereas underwater noise requires approaches linked to marine spatial management and the development of environmental thresholds under the MSFD. These differences demonstrate the need for approaches that combine common governance principles with pollutant-specific solutions.

Complementing these findings, the SOS-ZEROPOL2030 governance analysis (Van Leeuwen et al., 2023) highlights how pollution management is shaped by governance arrangements operating across the full pollutant and product lifecycle. It demonstrates the importance of coordination between policies, sectors and actors involved in production, use, end-of-life management and end-of-pipe measures.

A key conclusion from these assessments is that effective zero pollution approaches require a combination of source-based prevention and broader lifecycle perspectives. Addressing pollution at its origin, including through changes in production, use and end-of-life management, can significantly reduce emissions before they enter the environment.

However, source reduction alone may not be sufficient for pollutants associated with legacy contamination, continued releases or complex transport pathways, highlighting the continued importance of monitoring, mitigation and remediation approaches.

The governance analysis identifies source-based prevention and lifecycle approaches as important best practices, while also recognising barriers related to fragmented governance arrangements, interactions between sectoral policies, limited data availability and persistent legacy pollution (Van Leeuwen et al., 2023). Advancing zero pollution therefore requires clear and measurable objectives, robust knowledge and monitoring systems, stakeholder-inclusive policy development, policy coordination and evaluation, and cooperation beyond EU borders. Further strengthening regulatory frameworks, ensuring effective enforcement, integrating pollution and human health objectives, and fostering collaboration across sectors are essential to improve policy coherence and implementation. Empowering citizens and NGOs, improving access to pollution data and knowledge, and accounting for socio-economic considerations can further support transparent, inclusive and effective zero pollution policies (Devriese et al., 2025). However, effective implementation also depends on the perspectives of stakeholders, including the public, as well as implementation capacity and governance arrangements in practice. These dimensions are explored in the following section.

2.2. Stakeholder perspectives and co-created pathways for zero pollution

While the policy and governance analyses establish the strategic context for marine zero pollution, stakeholder engagement provides complementary evidence on how pollution risks, policy measures and implementation pathways are perceived by those responsible for, or affected by, pollution prevention and management. Within SOS-ZEROPOL2030, stakeholder engagement therefore formed a key component of the project's evidence base, providing insights into implementation challenges, governance barriers and opportunities for action across the source-to-sea continuum.

The stakeholder surveys conducted within the project examined public and stakeholder perceptions of four priority pollutant groups: microplastics, PFAS, eutrophication and underwater noise (Vaupotič et al., 2024). The surveys explored awareness, perceived risks and preferences for different policy interventions, including regulatory, technological and behavioural measures. Results showed that public concern was highest for microplastics, followed by PFAS, eutrophication and underwater noise, while awareness of underwater noise remained comparatively low. These differences highlight the importance of targeted communication and awareness-raising strategies as part of broader pollution prevention efforts.

Stakeholder responses provided additional insights into the acceptability and implementation challenges associated with different policy approaches. Across stakeholder groups, support was generally high for measures promoting environmentally friendly technologies and government-led ecosystem protection and restoration. However, preferences differed regarding regulatory instruments, economic incentives and the distribution of responsibilities among actors. These findings underline the importance of

combining technological innovation, regulatory measures, economic instruments and behavioural change. They also highlight that successful policy implementation depends on building trust in institutions and industry, as well as fostering cooperation among public authorities, industry, researchers and civil society.

Beyond surveys, SOS-ZEROPOL2030 applied participatory co-creation approaches through Regional Seas Living Labs and the Zero Pollution Parliament, bringing together stakeholders from different sectors and regions to explore pathways towards zero pollution and identify implementation challenges and trade-offs (Van Hulst et al., 2024; Van Hulst et al., 2025; Kopke et al., 2026). Using scenario-based discussions and the CO-ACT methodology, stakeholders consistently highlighted the need for proactive prevention complemented by targeted mitigation, supported by improved monitoring, stronger governance coordination, innovation and alignment between policy ambitions and implementation capacities.

The Living Labs further showed that solutions need to reflect pollutant-specific characteristics and regional contexts. For PFAS, stakeholders prioritised precautionary approaches, material substitution, improved monitoring and stronger enforcement, while recognising challenges related to legacy contamination. For TWPs, stakeholders emphasised lifecycle approaches, including improved product design, transparency across value chains, wastewater treatment and producer responsibility.

These stakeholder-driven processes complement the scientific and policy assessments by identifying practical implementation needs, governance barriers and enabling conditions. Together, they provide an essential evidence base for the transferable guidance and pollutant-specific recommendations presented in Chapters 4 and 5.

2.3. Pollutant-specific guidance foundations: PFAS and TWPs

The SOS-ZEROPOL2030 pollutant-specific guidance developed for PFAS and TWPs provides practical examples of how zero pollution approaches can be adapted to pollutants with different characteristics, emission pathways, governance challenges and levels of scientific understanding (Vlachogianni et al., 2026a; Vlachogianni et al., 2026b). Although PFAS and TWPs represent distinct pollution challenges, both demonstrate the importance of applying a source-to-sea and lifecycle perspective that addresses pollution prevention across production, use, release pathways and end-of-life management.

PFAS illustrate the challenges associated with persistent chemical contaminants that can remain in the environment for long periods, undergo long-range transport and accumulate across terrestrial, freshwater and marine ecosystems. Despite increasing regulatory attention and efforts to reduce emissions at source, important uncertainties remain regarding environmental concentrations, transport pathways, mixture effects and emerging PFAS compounds. The PFAS guidance therefore highlights the need for integrated approaches combining precautionary regulation, substitution, improved monitoring, emission control and coordinated action across stakeholders involved throughout the chemical lifecycle.

The guidance identifies source prevention as the most effective long-term strategy for reducing PFAS pollution, while recognising that continued monitoring, remediation and improved management of contaminated waste streams remain necessary due to legacy contamination and ongoing releases. Effective implementation requires strengthened knowledge systems, harmonised monitoring approaches, supply-chain transparency and collaboration between regulators, industry, researchers, infrastructure operators and civil society.

TWPs represent a different but complementary pollution challenge, as they are unintentionally generated through everyday activities and released continuously through tyre abrasion. Their diffuse emission pathways, including road runoff, atmospheric transport and wastewater systems, make them difficult to monitor and manage through traditional regulatory approaches. While knowledge gaps remain regarding environmental concentrations, sediment accumulation, toxicity and cumulative effects, TWPs highlight the challenges associated with managing widespread, continuously generated pollution sources.

The TWPs guidance demonstrates the need for interventions across the full source-to-sea pathway, combining source control through improved tyre design and standards, process control through mobility strategies and infrastructure measures, and end-of-pipe solutions to capture particles before they reach aquatic environments. At the same time, it emphasises that technological measures alone are insufficient and must be supported by harmonised monitoring, regulatory integration, stakeholder engagement and consideration of socio-economic implications.

Taken together, the PFAS and TWPs case studies demonstrate that, although effective zero pollution strategies must respond to pollutant-specific characteristics, they are underpinned by common governance principles centred on prevention, lifecycle and source-to-sea thinking, knowledge generation and integration, stakeholder engagement and adaptive implementation. These shared principles form the basis for the transferable guidance presented in Chapter 4, while the contrasting characteristics of PFAS and TWPs illustrate the need for differentiated implementation pathways.

2.4. Strategic implementation pathways towards zero pollution

Building on the policy analyses, stakeholder engagement and pollutant-specific guidance presented in the preceding sections, the SOS-ZEROPOL2030 Strategic Framework (Boteler et al., 2026) and Roadmap (Vlachogianni et al., 2026) integrate these complementary evidence and knowledge streams into a coherent strategic and operational approach for advancing zero pollution in European seas.

The EU Zero Pollution Action Plan, as a key component of the European Green Deal, establishes a long-term ambition to reduce pollution to levels that are no longer harmful to human health and ecosystems while remaining within planetary boundaries. This ambition is further reinforced by the European Ocean Pact, which highlights the need for targeted action to reduce marine pollution and strengthen marine governance. Despite the extensive EU policy framework addressing pollution prevention and reduction, marine

pollution remains a persistent challenge, requiring coordinated implementation pathways that translate strategic ambitions into concrete action.

Within this context, the SOS-ZEROPOL2030 Strategic Zero Pollution Framework and Roadmap provide the foundation for advancing zero pollution approaches in European seas. The Framework identifies objectives, targets, actions and cross-cutting stepping stones for addressing four priority pollutant groups: nutrients, hazardous substances, microplastics and underwater noise. It applies a source-to-sea perspective, recognising that effective pollution prevention requires consideration of pollutant sources, pathways, impacts and the roles of relevant actors across interconnected land, freshwater and marine systems.

The SOS-ZEROPOL2030 Roadmap translates this strategic vision into implementation pathways by identifying actions, responsible stakeholders, governance scales, implementation time horizons (2030, 2035 and 2040), and the enabling conditions required to support progress towards zero pollution. It bridges the gap between policy objectives and practical implementation by linking strategic ambitions with concrete measures and responsibilities.

Developed through a co-design process integrating scientific evidence, governance analyses, stakeholder engagement, Living Lab outcomes and SWOT assessments, the Roadmap considers not only environmental effectiveness but also implementation feasibility, governance capacity, barriers and opportunities for innovation and cooperation. The Roadmap functions as both a strategic planning framework and a decision-support tool, enabling stakeholders to identify relevant actions according to pollutant type, objectives, responsibilities and implementation timeframe.

Together, the Framework and Roadmap provide the basis for this guidance. They connect the transferable governance principles and pollutant-specific recommendations presented in the following chapters with the implementation pathways, governance arrangements and enabling conditions needed to translate zero pollution ambitions into coordinated action and measurable improvements for European seas.

3. Cross-Cutting Challenges and Rationale for Transferable Guidance

3.1. Marine pollution as a systemic and interconnected challenge

Marine pollution is a complex challenge that extends beyond geographical, administrative and sectoral boundaries. Marine ecosystems are connected with terrestrial and freshwater environments through physical, chemical and biological processes, meaning that many pollutants affecting European seas originate from activities occurring far from the marine environment. Pollutants can reach coastal and marine waters through rivers, groundwater, atmospheric deposition, runoff and other transport pathways, highlighting the need for approaches that consider the full source-to-sea continuum.

The four priority pollutant groups addressed within SOS-ZEROPOL2030 – nutrients, hazardous substances, microplastics and underwater noise – illustrate the diversity and complexity of marine pollution challenges. These pollutants differ in their sources, emission pathways, environmental behaviour, spatial distribution and ecological effects. While some pressures may be reduced relatively quickly through effective emission controls, others, such as persistent chemical contaminants, may continue to affect ecosystems due to environmental accumulation and legacy contamination. Similarly, diffuse pollution sources require different management approaches compared with identifiable point sources.

These differences demonstrate that achieving zero pollution requires a combination of pollutant-specific measures and broader governance approaches that can be applied across different pollution contexts. At the same time, uncertainties relating to emissions, transport pathways, cumulative effects and ecosystem responses require adaptive governance supported by monitoring, knowledge generation and continuous learning.

3.2. Common governance challenges across pollutant groups

Despite important differences between pollutant groups, the evidence synthesised throughout SOS-ZEROPOL2030 identifies several recurring governance challenges that influence the effectiveness of marine pollution prevention and reduction efforts.

Knowledge gaps and monitoring limitations: Effective pollution management depends on reliable information on sources, pathways, environmental concentrations and trends, impacts and mitigation effectiveness. However, knowledge availability differs considerably between pollutants and regions, particularly for emerging contaminants and diffuse sources. These uncertainties can limit target setting, prioritisation of measures and evaluation of progress. Reliable baseline data, harmonised monitoring and accessible data infrastructures provide the foundation for defining environmental conditions, tracking progress towards policy objectives and evaluating the effectiveness of implemented measures. To effectively support decision-making and enable coherent assessments across regions, monitoring systems and methods must be strengthened and scientific evidence made accessible and relevant to policy needs. Their effectiveness, however, also

depends on clear and measurable policy targets against which baselines can be established, progress assessed and implementation adapted where necessary.

Policy coherence and coordination: Marine pollution is addressed through multiple policy frameworks covering different environmental compartments, sectors and governance levels. While instruments such as the Marine Strategy Framework Directive, Water Framework Directive, REACH Regulation and Waste Framework Directive provide important foundations, fragmented responsibilities and sectoral approaches can create challenges for coherent implementation. A source-to-sea perspective is therefore needed to connect upstream activities with downstream environmental impacts and ensure alignment between policies. In addition, clear allocation of roles and responsibilities across relevant actors and governance levels is essential to ensure accountability and effective policy implementation.

Prevention and lifecycle-based intervention: Across pollutant groups, preventing pollution at source is a central principle for achieving long-term reductions. However, effective intervention requires understanding pollutant lifecycles, from production and use through release pathways, transport and environmental fate. Depending on the pollutant, this may involve regulatory restrictions, material substitution, cleaner production processes, behavioural changes, technological innovation or improved waste and wastewater management. Clear objectives linked to specific pollutants and their emission sources can help guide the selection and prioritisation of prevention measures. The most appropriate combination of measures will depend on their environmental effectiveness, feasibility and stakeholder capacities.

Stakeholder engagement and implementation capacity: Zero pollution strategies require cooperation between policymakers, competent authorities, industry, researchers, infrastructure providers and civil society. Stakeholder involvement is essential not only for improving acceptance but also for identifying practical barriers, responsibilities and opportunities for implementation. SOS-ZEROPOL2030 stakeholder activities demonstrate that technically effective measures must also consider governance capacity, economic implications and stakeholder perspectives to achieve lasting impact. Transparent and inclusive engagement processes that strengthen the science-policy-society interface, combined with awareness raising, can further support informed decision-making and facilitate the effective implementation of pollution prevention measures.

Adaptive governance and long-term implementation: Achieving zero pollution is a long-term transition requiring continuous evaluation and adjustment. Scientific developments, technological innovation, changing socioeconomic conditions and emerging pressures may require adaptation of policies and measures over time. Effective governance therefore depends on mechanisms for monitoring progress, evaluating outcomes and updating actions based on new knowledge. This, in turn, requires coordinated policy evaluation frameworks that align EU objectives with sectoral policies, ensure effective implementation and compliance, and support proactive responses to emerging contaminants and cumulative pressures affecting marine ecosystems.

3.3. From shared challenges to transferable guidance

The recurring governance challenges identified across pollutant groups demonstrate that achieving zero pollution cannot rely solely on pollutant-specific interventions. While technical measures must be tailored to the characteristics of individual pollutants, progress also depends on common governance principles that strengthen prevention, policy coherence, knowledge integration, stakeholder engagement and adaptive implementation. These shared principles provide the rationale for the transferable guidance presented in Chapter 4, which translates the project's evidence base into practical recommendations applicable across different pollutant groups and governance contexts.

4. Cross-Cutting Transferable Guidance for Marine Zero Pollution

The analyses presented in Chapters 2 and 3 demonstrate that, although pollutant groups differ in their sources, pathways and impacts, they share many common governance and implementation challenges. Across pollutants, effective action depends not only on pollutant-specific technical measures but also on governance arrangements that support prevention, policy coherence, adaptive management, knowledge integration, innovation and stakeholder collaboration. The following guidance synthesises these common principles into a set of transferable actions that can strengthen implementation of the EU Zero Pollution ambition across different pollutant groups, geographical contexts and governance levels.

4.1. Actionable guidance

4.1.1. Strengthen cross-sectoral cooperation and governance

Marine pollution is governed through a wide range of sectoral policies and institutions spanning chemicals, water, waste, agriculture, transport, industry, public health and marine environmental protection. Strengthening cooperation across these domains is essential to improve policy coherence and ensure that measures implemented in one sector contribute to, rather than undermine, broader zero pollution objectives.

Recommended actions include:

- Support permanent European communities of practice that bring together policymakers, regulators, researchers, industry, civil society and Regional Sea Convention representatives to exchange knowledge and implementation experience.
- Create thematic expert working groups for priority pollutant groups that incorporate expertise from different scientific disciplines, including human and environmental health, governance and relevant economic sectors, where relevant.
- Clarify roles and responsibilities across relevant actors and governance levels to support accountability and the effective implementation of zero pollution measures.
- Strengthen coordination between European, national, regional and local authorities responsible for pollution prevention and marine environmental management.
- Strengthen implementation by improving coordination and alignment across existing European, national and regional policy frameworks before introducing new governance mechanisms.
- Promote systematic exchange of good practices, implementation experiences and lessons learned across Member States.
- Strengthen cooperation with Regional Sea Conventions to support coordinated implementation across shared marine regions and address transboundary pollution pressures.

4.1.2. Prioritise prevention through source control and lifecycle approaches

Across all pollutant groups examined in SOS-ZEROPOL2030, prevention consistently emerged as the most effective long-term strategy for reducing pollution. While remediation and end-of-pipe measures remain necessary in some cases, particularly for legacy pollution, preventing pollutant releases at source generally provides greater environmental benefits, lower long-term costs and fewer unintended consequences.

Recommended actions include:

- Prioritise upstream interventions that prevent pollutant releases before they enter aquatic environments.
- Apply source-to-sea thinking to the design, implementation and coordination of policies and measures, recognising the connectivity between terrestrial, freshwater, coastal and marine systems.
- Integrate lifecycle approaches into policy development by considering pollutant generation, production, use, transport, disposal and environmental fate.
- Promote pollution prevention through design by encouraging eco-design and Safe and Sustainable by Design approaches, including the substitution of hazardous materials with safer and more sustainable alternatives, alongside sustainable infrastructure, cleaner production systems and innovation that minimise pollution generation throughout product and infrastructure lifecycles.
- Encourage the use of economic instruments and extended producer responsibility schemes where these can support pollution prevention.
- Apply precautionary approaches where scientific evidence indicates significant environmental risks despite remaining uncertainties.

4.1.3. Improve monitoring, knowledge integration and adaptive management

Achieving zero pollution requires robust evidence on pollutant sources, environmental pathways, ecological impacts and policy effectiveness. Although monitoring capacities continue to improve, important gaps remain regarding emerging pollutants, cumulative pressures, transboundary pollution and long-term environmental responses. Monitoring systems should therefore support not only compliance assessment but also continuous learning and adaptive management.

Recommended actions include:

- Harmonise monitoring methodologies, indicators and reporting approaches across Member States wherever possible.
- Define clear, measurable objectives and indicators for specific pollutants, sources and pressures to support progress assessment, accountability and effective policy implementation.
- Improve the interoperability and accessibility of environmental datasets across monitoring programmes and policy domains.
- Strengthen monitoring of emerging pollutants, cumulative impacts and source-to-sea pollutant pathways.

- Expand integrated policy tracking and assessment mechanisms that support monitoring of implementation progress, policy coherence and compliance across the source-to-sea continuum, building on existing initiatives such as the European Environment Agency's Zero Pollution Monitoring Tool and the future EU Ocean Dashboard.
- Promote the use of digital technologies, including Earth observation, interoperable data platforms, artificial intelligence, digital twins and predictive models, to strengthen monitoring, forecasting and evidence-based decision-making.
- Establish regular mechanisms for reviewing policy effectiveness and updating measures as new scientific evidence becomes available.
- Address key knowledge gaps relating to pollutant sources, environmental fate, human health implications, cumulative impacts and transboundary pollution.
- Apply adaptive governance approaches that regularly review monitoring results, policy effectiveness and implementation experience to update measures as scientific knowledge, technologies and environmental conditions evolve.
- Strengthen compliance and enforcement mechanisms by linking monitoring outcomes with implementation reviews and corrective actions where objectives are not being achieved.

4.1.4. Strengthen science-policy interfaces and stakeholder engagement

The stakeholder engagement activities undertaken within SOS-ZEROPOL2030 demonstrated that effective implementation depends not only on scientific evidence but also on stakeholder acceptance, institutional capacity and practical feasibility. Integrating scientific knowledge with stakeholder knowledge and practical experience improves the relevance, legitimacy and implementability of zero pollution policies.

Recommended actions include:

- Strengthen mechanisms that facilitate regular dialogue between researchers, policymakers, regulators, industry and civil society.
- Improve the communication of scientific evidence, including uncertainties, in formats that support policy development and implementation.
- Develop accessible public information platforms that communicate pollution sources, environmental and human health risks, and progress towards zero pollution using clear, evidence-based information.
- Support stakeholder participation throughout policy design, implementation and evaluation, particularly where measures involve behavioural change or shared responsibilities.
- Promote capacity building, peer learning and knowledge exchange to strengthen implementation capacity across governance levels and sectors.

4.1.5. Strengthen policy coherence and international cooperation

Many pollutants affecting European seas originate beyond the marine environment or cross administrative and national boundaries before reaching coastal waters. Achieving

zero pollution therefore requires coherent implementation across policy frameworks and sustained cooperation at regional and international levels.

Recommended actions include:

- Improve alignment between legislation addressing marine protection, water quality, chemicals, waste, product design, agriculture, transport and industrial emissions.
- Embed the source-to-sea approach within the implementation of existing European, national and regional policy frameworks to strengthen coordination across environmental compartments and governance levels.
- Develop and promote practical guidance and best practices that support implementation of the source-to-sea approach across existing European, national and regional policy frameworks.
- Combine regulatory measures with financial incentives, public procurement, market-based instruments and innovation funding to accelerate implementation and encourage uptake of pollution prevention measures.
- Evaluate potential trade-offs and unintended consequences of pollution prevention measures using systems-based approaches that minimise burden shifting across pollutants, sectors and environmental compartments.
- Promote research and innovation that strengthen governance, policy design, implementation and evaluation, alongside technological innovation.
- Support international cooperation through Regional Sea Conventions and other regional governance mechanisms.
- Continue European leadership in international initiatives addressing marine pollution, including global agreements on plastics, hazardous chemicals and other transboundary pollution issues.
- Encourage greater coordination between environmental, climate, biodiversity and circular economy policies to maximise co-benefits and reduce unintended trade-offs.

4.2. Concluding remarks

The transferable guidance presented in this chapter synthesises the policy, governance and stakeholder evidence generated throughout SOS-ZEROPOL2030 into a set of cross-cutting governance actions applicable across multiple pollution challenges. While individual pollutants require tailored technical interventions, the analyses consistently demonstrate that progress towards marine zero pollution depends on a common set of enabling conditions: stronger cooperation across sectors and governance levels, clear objectives and responsibilities, greater emphasis on prevention, integrated monitoring and knowledge systems, robust evidence to support target setting and policy evaluation, effective science-policy interfaces, meaningful stakeholder participation, and coherent implementation across policy domains. Embedding these governance approaches within future policy development and implementation can help accelerate progress towards the EU's Zero Pollution ambition while strengthening the effectiveness, coherence and long-term resilience of marine pollution governance.

5. Pollutant-Specific Requirements and Future Pathways for Zero Pollution in European Seas

Although marine pollutants share common governance challenges and require coordinated approaches based on prevention, knowledge integration and adaptive management, the characteristics of individual pollutant groups strongly influence the type, scale and timing of effective interventions. Differences in emission pathways, persistence, mobility, environmental behaviour and societal drivers determine where interventions are most effective and which actors need to be involved.

The analysis conducted within SOS-ZEROPOL2030 demonstrates that achieving zero pollution in European seas cannot rely on a single management model. While transferable principles provide a common framework for action, implementation pathways need to be adapted to pollutant-specific characteristics, including whether pollution originates from diffuse or point sources, whether emissions can be prevented at source, whether legacy contamination persists after emission reductions, and whether solutions depend primarily on technological innovation, regulatory action, behavioural change or improved governance coordination.

This section summarises the key pollutant-specific requirements identified for the four priority pollutant groups addressed in SOS-ZEROPOL2030. It highlights how common zero pollution principles can be translated into tailored pathways, while considering future scenarios, emerging pressures and opportunities for strengthening marine pollution prevention in the EU.

5.1. Persistent hazardous substances: strengthening prevention and managing legacy pollution

Persistent hazardous substances, including PFAS, represent a particular challenge due to their persistence, long-range transport potential and ability to accumulate in environmental compartments and biota. Unlike pollutants where reductions in emissions may rapidly translate into improvements in environmental quality, persistent substances may continue to pose risks long after releases have been reduced.

For these pollutants, achieving zero pollution requires prioritising upstream prevention and substitution, supported by stronger regulatory control, improved transparency on chemical use and enhanced monitoring. The most effective interventions occur before chemicals enter production and consumption systems, through restrictions on unnecessary uses, development of safer alternatives and improved information throughout supply chains.

However, prevention alone is insufficient because historical emissions and existing contamination may continue to affect marine environments. Pollutant-specific pathways therefore need to combine source reduction with improved understanding of environmental reservoirs, exposure pathways and options for managing contaminated sites.

Key requirements for effective management of persistent chemical pollutants include:

- strengthening precautionary approaches for persistent and hazardous substances;
- improving secure information exchange throughout chemical value chains, including data on production, use, emissions, product composition and imported products;
- accelerating substitution where safer alternatives are available;
- embedding Safe and Sustainable by Design principles in chemical and product development, procurement and industrial innovation;
- improving monitoring approaches to detect emerging contaminants and evaluate progress;
- strengthening coordination between chemical, water, waste and marine policies;
- addressing legacy contamination through targeted remediation and risk management approaches.

Future zero pollution pathways for persistent chemicals will depend increasingly on integrating chemical safety objectives with circular economy approaches and ensuring that new substances entering markets are assessed not only for their intended use but also for their long-term environmental consequences.

5.2. Nutrient pollution: integrating land-based pressures and ecosystem management

Nutrient pollution differs from many chemical pollutants because nutrients are essential components of ecosystems but become harmful when inputs exceed natural assimilative capacity. Excess nitrogen and phosphorus inputs remain among the major pressures affecting European marine ecosystems, contributing to eutrophication, oxygen depletion and ecosystem degradation.

The main challenge for nutrient management is the diffuse and interconnected nature of sources, particularly agriculture, wastewater, atmospheric deposition and urban runoff. Effective pathways therefore require a strong source-to-sea approach, connecting terrestrial management decisions with downstream marine impacts.

For nutrient pollution, achieving zero pollution does not necessarily mean eliminating nutrient inputs, but rather achieving balanced nutrient cycles through improved efficiency, prevention of excessive losses and restoration of ecosystem capacity.

Key requirements include:

- reducing nutrient losses at source through sustainable agricultural practices and improved nutrient management;
- reducing atmospheric nitrogen emissions and deposition through coordinated measures across agriculture, energy, industry and transport;
- closing nutrient loops through phosphorus recovery, organic-waste recycling and safe regional reuse systems;
- improving wastewater treatment performance and reducing urban runoff impacts;
- strengthening integration between agricultural, water and marine policies;

- improving catchment-to-coast monitoring and modelling approaches;
- considering cumulative impacts, regional ecosystem characteristics and potential pollution swapping between air, soil, water and climate objectives;
- supporting nature-based solutions that enhance nutrient retention and ecosystem resilience.

Future pathways need to account for changing pressures, including climate change, altered precipitation patterns and agricultural transformation. Scenario-based approaches are therefore essential to evaluate how combinations of measures can deliver effective nutrient reductions while maintaining food production and economic viability.

5.3. Microplastics: addressing diffuse emissions across product lifecycles

Microplastics represent a highly diverse pollutant group characterised by multiple sources, pathways and emission mechanisms. Unlike pollutants associated with a limited number of industrial activities, microplastic pollution results from a wide range of products, activities and consumer behaviours, including tyre and road wear particles, textile fibre emissions and plastic pellet losses.

Because emissions occur throughout product lifecycles, effective management requires moving beyond end-of-pipe solutions towards integrated prevention strategies. This includes reducing emissions during production and use, improving product design, strengthening waste and wastewater management, and increasing transparency across supply chains.

Different microplastic sources require different intervention pathways:

Tyre and road wear particles require integrated transport and urban management approaches, combining improved tyre design, road infrastructure measures, stormwater management, wastewater treatment and mobility strategies.

Synthetic textile fibres require lifecycle interventions addressing textile design, washing processes, consumer behaviour and circular textile systems.

Plastic pellets require stronger supply-chain accountability, containment measures, monitoring and traceability systems to prevent accidental losses during production and transport.

Key requirements include:

- applying lifecycle-based approaches from product design to end-of-life;
- strengthening harmonised product standards, test methods, environmental performance criteria, labelling and market-surveillance mechanisms;
- integrating microplastic prevention into urban drainage, stormwater, road-infrastructure and wastewater investment planning;
- ensuring that captured particles and contaminated residues are safely managed to prevent secondary releases;
- improving monitoring methodologies for different microplastic sources;
- combining regulatory measures with innovation and behavioural approaches;

- improving capture technologies where prevention is not immediately possible;
- strengthening producer responsibility and supply-chain transparency.

Future pathways will increasingly depend on integrating microplastic prevention into broader circular economy, sustainable production and consumption, and urban management strategies.

5.4. Underwater noise: managing a non-material pollutant through spatial and operational measures

Underwater noise represents a distinct pollution challenge because it is an energy-based pressure rather than a substance accumulating in the environment. Its impacts depend strongly on intensity, frequency, duration and timing, as well as the sensitivity and distribution of marine species.

Unlike many chemical pollutants, underwater noise can often be reduced relatively quickly when emission sources are controlled. However, effective management requires coordination across maritime sectors because sources are distributed across shipping, offshore energy, construction, fisheries and other activities.

For underwater noise, zero pollution pathways require a combination of source control, operational management, spatial planning and improved monitoring.

Key requirements include:

- reducing noise emissions at source through quieter vessel design and technologies;
- integrating underwater noise considerations into maritime spatial planning;
- applying spatial and operational measures, including quiet zones, routing, speed management and seasonal or area-based restrictions in ecologically sensitive locations;
- establishing vessel-noise baselines and harmonised measurement protocols to support consistent assessment and management;
- improving monitoring networks and harmonising assessment methodologies;
- strengthening coordination between maritime sectors and environmental authorities;
- developing harmonised noise-performance indices and linking them, where appropriate, to port fees, priority berthing, environmental labelling and other incentives for quieter vessels and operations;
- improving awareness and capacity within maritime industries.

Future pathways will depend on integrating underwater noise into broader maritime sustainability frameworks, including ship performance assessment, green port initiatives and environmental decision-making. The development of harmonised indicators and reporting approaches will be particularly important to support consistent implementation across European seas.

5.5. Integrating pollutant-specific pathways into future zero pollution scenarios

The pollutant-specific assessments demonstrate that future pathways towards zero pollution require differentiated strategies rather than uniform solutions. Persistent chemical contaminants require upstream prevention, substitution and management of legacy contamination; nutrient pollution requires integrated catchment, atmospheric and ecosystem management; microplastics require lifecycle interventions across products, infrastructure and diffuse release pathways; and underwater noise requires spatial, operational and design-based measures supported by harmonised acoustic assessment.

These differences affect the timing, scale and combination of interventions required. They also determine which actors, infrastructures and regulatory instruments are most relevant. The pollutant-specific pathways therefore complement the transferable guidance in Chapter 4 by showing how common principles must be adapted to the distinct characteristics and management needs of each pollutant group.

6. Conclusions and implications for strengthening marine zero pollution pathways

Achieving zero pollution in European seas requires moving beyond exclusively pollutant-specific management towards integrated strategies that address the interconnected nature of pollution sources, pathways and impacts. The analysis undertaken within SOS-ZEROPOL2030 demonstrates that, despite important differences between pollutant groups, several common conditions shape the effectiveness of pollution prevention and reduction efforts.

A source-to-sea perspective emerges as a central principle for future marine pollution governance. Many pressures affecting marine ecosystems originate from activities and decisions outside the marine environment, requiring stronger coordination between environmental, sectoral and economic policies. Effective action therefore depends on improved policy coherence, robust knowledge and monitoring systems, clear objectives and responsibilities, meaningful stakeholder engagement and adaptive governance.

At the same time, transferable principles must be complemented by pollutant-specific pathways. Persistent chemicals require strong prevention and substitution alongside management of legacy contamination; nutrients require integrated catchment-to-coast and atmospheric management; microplastics require lifecycle-based interventions addressing multiple diffuse sources; and underwater noise requires coordinated spatial, operational and source-control measures.

Progress will depend on combining regulatory action, technological innovation, behavioural change and strengthened governance capacity. Scenario-based approaches can help assess how different combinations of measures may influence progress towards environmental objectives, identify trade-offs and support the prioritisation of interventions under changing environmental and socioeconomic conditions. Continuous evaluation of progress, supported by reliable evidence and stakeholder input, will be essential to refine measures and ensure that policy ambitions remain achievable and effective over time.

The guidance developed in this deliverable links common governance principles with pollutant-specific implementation needs. The analyses undertaken within SOS-ZEROPOL2030 indicate that future progress towards marine zero pollution depends less on identifying new environmental objectives than on strengthening the coordinated implementation of existing policy ambitions across the source-to-sea continuum. By providing scientifically informed, practically feasible and implementation-oriented guidance, this deliverable supports policymakers and other stakeholders in translating the EU Zero Pollution ambition into coordinated action across interconnected terrestrial, freshwater and marine systems. Achieving lasting reductions in marine pollution will ultimately depend on sustained coordination across the source-to-sea continuum and the capacity to adapt responses as pressures and knowledge evolve.

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