Ocean Decade

Vision 2030

White Papers

Challenge 1:

Understand and beat marine pollution

The United Nations
Decade of Ocean Science
for Sustainable Development
(2021-2030)

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Ocean Decade Vision 2030 White Papers

Challenge 1: Understand and beat marine pollution

Understand and map land- and sea-based sources of pollutants and contaminants and their potential impacts on human health and ocean ecosystems, and develop solutions to remove or mitigate them.

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Contents

Acronyms

BATS	Bermuda Atlantic Time-series Study
CARE	Collective benefit, Authority to control, Responsibility, Ethics
FAIR	Findable, Accessible, Interoperable, Reusability
GEOTRACES	An international programme which aims to improve the understanding of biogeochemical cycles and large-scale distribution of trace elements and their isotopes in the marine environment.
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
GO-SHIP	Global Ocean Ship-Based Hydrographic Investigations Program
Hg	Mercury
IAEA	International Atomic Energy Agency
IMOS	Integrated Marine Observing System
IOC	Intergovernmental Oceanographic Commission
IODE	International Oceanographic Data and Information Exchange
IPCC	Intergovernmental Panel on Climate Change
NGO	Non-Governmental Organization
ODIS	Ocean Data and Information System
OBPS	Ocean Best Practices System
PAHs	Polycyclic Aromatic Hydrocarbons
PFAA	Per- and polyfluoroalkyl substances
POPs	Persistent Organic Pollutants
SIDS	Small Island Developing States
SROCC	Special Report on the Ocean and Cryosphere in a Changing Climate
UN	United Nations
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
WOA	World Ocean Assessment

1. EXECUTIVE SUMMARY

1.1 Introduction and Scope of the White Papers

This White Paper has been prepared as part of the Vision 2030 process being undertaken in the framework of the UN Decade of Ocean Science for Sustainable Development. The Vision 2030 process aims to achieve a common and tangible measure of success for each of the ten Ocean Decade Challenges by 2030. From a starting point of existing initiatives underway in the Ocean Decade and beyond, and through a lens of priority user needs, the process determines priority datasets, critical gaps in science and knowledge, and needs in capacity development, infrastructure and technology required for each Challenge to ensure that it can be fulfilled by the end of the Ocean Decade in 2030.

The results of the process will contribute to the scoping of future Decade Actions, identification of resource mobilization priorities, and ensuring the ongoing relevance of the Challenges over time. The process identifies achievable recommendations that can be implemented in the context of the Decade, or more broadly before 2030 to achieve the identified strategic ambition and indicators that will be used to measure progress.

This White Paper is one of a series of ten White Papers all of which have been authored by an expert Working Group. Accompanied by an Outcomes Report authored by the Decade Coordination Unit, this White Paper was discussed at the 2024 Ocean Decade Conference before being finalized and published.

1.2 Strategic Ambition of Ocean Decade Challenge No. 1

By 2030, the success of Ocean Decade Challenge No.1 'Understand and Beat Marine Pollution' will be demonstrated by the generation of scientifically sound data enabling a holistic understanding of the extent and impact of pollution across the land-ocean continuum, thereby supporting the achievement of a cleaner and healthier ocean where all ecosystems and their inhabitants thrive free from the impacts of marine pollution, allowing for their full functioning and service provision. This success will be based on completion of a comprehensive review of all available evidence about marine pollution, including an analysis of data gaps and the development and implementation of strategies for filling those gaps, as well as a comprehensive analysis of solutions for addressing and preventing the negative effects of marine pollution. Achieving this success will require knitting together existing and new data sets using AI and other technologies, identifying priority pollutants and areas for action, and providing globally consistent monitoring, data collection, storage and sharing protocols. Success will further be demonstrated through the establishment of new connections and partnerships among users across the public - private spectrum that lead to the funding, development and implementation of new technologies and projects aimed at monitoring, controlling, reducing, and/or mitigating marine pollution from any source, including the creation and sustainability of a global network of strategically positioned sentinel stations and regional laboratory hubs for sustained, long-term monitoring of marine pollution.

Success will include fulfilment of the following critical knowledge gaps:

- a comprehensive and holistic understanding of the impacts of priority pollutants (e.g., pollutants found or expected to emerge in high concentrations, or with high toxicity, or with significant adverse effects on biota or human health) across the land to ocean continuum;
- a better understanding of the sources, sinks, fate and impacts of all pollutants, including the pollutants of emerging concern;
- improved knowledge on the distribution and impacts of marine pollution, particularly in the Global South and deep

ocean waters, which currently represent the largest geographical gaps.

and the following priority datasets gaps:

- long-term time series of marine pollutants;
- baseline and toxicity data of pollutants across the land-ocean continuum;
- data on the impacts of the co-occurrence of multiple pollutants;
- data on the effects of climate change on the toxicity, bioavailability and impacts of multiple co-existent pollutants.

It will include development of:

- a global network of strategically positioned sentinel stations for continuous, long-term monitoring;
- cost-effective, real-time monitoring systems and technologies for tracking pollutant sources, distribution, and transfers across the land-ocean continuum;
- a global network of regional laboratory hubs focused on generating high-quality data, promoting capacity building and facilitating technology transfer;
- training programs on harmonized protocols for the acquisition, reporting and recording of quality-controlled data on marine pollution;
- environmentally robust new technologies and processes for the control and mitigation of marine pollution.

1.3 Key Recommendations to Achieve the Strategic Ambition

The following recommendations have been identified to ensure that the strategic ambition is fulfilled, and success achieved for Ocean Decade Challenge No. 1.

It is recommended that:

1. By 2025, a Decade Coordinating Centre specifically focusing on marine pollution is established as a central mechanism for coordinating existing and future Decade Actions dealing with marine pollution and for coordinating establishment of a network of scientists and other users to define priority pollutants, construct harmonized protocols for rigorous monitoring of marine pollution and define the specifications and operational conditions of sentinel monitoring stations.
2. By 2026, the scientific community has completed the design of harmonized protocols for rigorous monitoring of marine pollution and has defined the specifications and operational conditions of sentinel monitoring stations.
3. By 2028, the scientific community has completed a comprehensive review of existing literature and datasets to identify relevant data on the distribution, fate, toxicity, and impacts of marine pollution across the land-ocean continuum.
4. By 2029, the Ocean Decade has full and visible participation in the OceanObs'29 Conference to be hosted in China in 2029, to ensure the seamless integration of marine pollution, biology, and ecosystem operations, research, and applications into the framework for ocean observing.
5. By 2030, the scientific community together with resource providers, governmental and intergovernmental agencies and organizations, treaty and convention bodies, and local communities, have established a global network of long-term sentinel stations to monitor marine pollution.
6. By 2030, public-private partnerships involving academia, resource providers, governmental and inter-governmental agencies and organizations, regional organizations, and treaty and convention bodies have established a network of regional laboratory hubs. These hubs will operate the long-term sentinel stations for monitoring of marine pollution, support the generation of high-quality data, promote capacity building, and facilitate the transfer of technology.

1.4 Key Milestones and Indicators for the Strategic Ambition

The key milestones and indicators that will be used to measure the fulfilment of the strategic ambition include:

1. Societal and Environmental Impact
    - By 2026 - The scientific community, in collaboration with marine-dependent and local communities and under the coordination of UN entities, supported by the Decade Collaborative Centre on Marine Pollution, will define a priority pollutants list and the scope of a comprehensive data and knowledge gap analysis.
    - By 2028 - Completion of the analysis of data and knowledge gaps and development of strategies for closing them based on the review of the literature and available databases by the scientific community coordinated by UNESCO-IOC.
    - By 2029 - Completion of Decade Actions involving the scientific community together with UN entities and governmental agencies that identify key pollutant threshold risks, for different environmental compartments, focusing on impact, to assess global ocean health.
    - By 2030 - Completion of Decade Actions involving the scientific and academic communities, coordinated by UN entities and governmental agencies, for comprehensive assessments of the interplay between pollutants and climate change, examining combined impacts on marine ecosystems and biodiversity.
    - By 2030 - Development, through targeted Decade Actions, of harmonized protocols for sound scientific decision-making regarding marine pollution by policymakers, local communities, academia, and NGOs.
2. Enhanced Ocean Data Accessibility and Availability
    - By 2025 – Establishment of a network of scientists to discuss and construct harmonized protocols or robust, rigorous, and scientifically sound monitoring and data sharing of marine pollutants, to be coordinated by UNESCO-IOC.
    - By 2026 – Establishment of an inter-regional multi-stakeholder committee to define specifications and operational conditions for the number, location, establishment and operation, and maintenance of sentinel monitoring stations, including the definition of the priority pollutants, along with terms of reference for ongoing monitoring to ensure implementation of these specifications and operational conditions.
    - By 2027 – Call by UNESCO-IOC for institutions interested in becoming a regional laboratory hub to support sentinel stations.
    - By 2028 - the Ocean Decade has full and visible participation in the OceanObs'29 Conference to be hosted in China in 2029, to ensure the seamless integration of marine pollution, biology, and ecosystem operations, research, and applications into the framework for ocean observing.
    - By 2030 – Commencement of implementation of long-term monitoring program in sentinel stations by UNESCO-IOC.
    - By 2030 – Construction of consolidated regional and global databases of marine pollution to be hosted by an UN agency.
3. Building Capacity for Understanding and Beating Marine Pollution
    - By 2026 - Design training sessions to implement harmonized protocols for the production, collection, analysis, interpretation, dissemination, and management of marine pollution data.

These sessions will ensure completeness, timeliness, interoperability, and quality of data generation, dissemination, and management by scientists and other stakeholders.

- By 2026 - Implement Decade Actions involving academic communities, local communities, NGOs, UN entities, and resource providers to deliver training programs focused on disseminating harmonized protocols. These programs will support the sound generation, management, interoperability and sharing of data and knowledge, with particular emphasis on developing and least developed countries.
- By 2030 – Member states, resource providers, resources managers, UN entities, academia, Regional Seas conventions and other regional environmental bodies should establish a network of regional marine pollution laboratory hubs for monitoring, training, and data/knowledge sharing. This network should focus on addressing the geographical gap in the Global South (e.g., data and expertise), particularly in developing and least developed countries.

4. Advancement in Ocean Technology and Innovation

- By 2026 – Completion of Decade Actions involving scientists, academia, NGOs, the private sector, resource managers, and providers focusing on the analysis of technology and innovation gaps for monitoring pollutants.
- By 2027 – Production of lists of recommended approaches, including instrumentation and software for screening and target pollution measurements and/or analysis.
- By 2028 – Completion of a wide range of Decade Actions, predominantly at the project level, involving academia, NGOs, the private sector, local communities, and resource providers, specifically targeted at the ongoing development of robust, innovative, and cost-effective technologies and devices for screening and monitoring pollution across the land-ocean continuum, including the development of associated harmonized protocols.
- By 2030 – Completion of Decade Actions involving academia, local communities, governmental, and intergovernmental agencies aimed at the implementation and global adoption of robust, innovative, and cost-effective technologies for monitoring pollution across the land-ocean continuum.
- By 2030 – Completion of Decade Actions and securing ongoing support levels by the private sector, resource managers, and resource providers involving the development of new, cost-effective technologies to mitigate marine pollution at local, regional, and global levels.

2. INTRODUCTION

2.1 Background and context of the Challenge

The ocean and its ecosystems provide significant benefits to humans, including climate regulation, food, coastal protection, employment, and recreation, as well as cultural and physical well-being (IPCC SROCC, 2019). However, the marine environment is under increasing threat from the cumulative negative impacts of human activities. Many ocean and coastal ecosystems are severely degraded and in need of immediate remedial action (WOAI, 2016; WOAII, 2021). One of the primary causes of this degradation is marine pollution. A threat in its own right, marine pollution also compounds the adverse impacts from other environmental threats, including biodiversity loss (Challenge 2) and climate change (Challenge 5).

Marine pollution is the presence or introduction into the environment of substances and energy that cause adverse effects on human health, the environment or living organisms; or that exceed the quality criteria established for certain environmental media (UN EMG, 2023).

Any substance or energy emanating from any source – be it terrestrial, marine, or atmospheric – may be a potential pollutant. What matters is the actual or potential impact that the introduction of a particular substance or energy has on human health, marine organisms, and ecosystem services and functions.

A wide array of substances and forms of energy are now recognized as marine pollutants (Figure 1), including, for example:

- chemicals, such as metals, persistent organic pollutants (POPs) listed in the Stockholm Convention on Persistent Organic Pollutants, as well as other POPs identified as priority substances (e.g., polycyclic aromatic hydrocarbons (PAHs) and perfluorinated alkyl substances (PFAS)), fertilizers, pharmaceuticals (e.g., hormones, personal care products, antibiotics), and plasticizers;
- oil and other petroleum-based products, such as plastics which are currently the subject of international negotiations towards a global treaty aimed, among other things, at stopping their flow into the ocean;
- industrial and domestic effluents, as well as mine tailings and agricultural runoff;
- biologically active materials, such as excess nutrients, fecal bacteria, pathogens, and antimicrobial resistant bacteria;
- suspended sediments;
- natural and artificial radionuclides;
- energy, including noise and light.

However, while the above examples include some of the thousands of substances and energy sources in use, they do not encompass the entire spectrum of actual and potential pollutants, many of which may only be discovered to have caused environmental impacts years after their introduction into the environment.

Most marine pollution originates from land-based sources and enters the marine environment through various pathways, including urban and agricultural run-off, estuarine and groundwater systems, as well as discharge of untreated sewage, mining and industrial effluents, and atmospheric deposition of airborne particles. Additionally, marine-based activities including shipping, resource extraction, shipwrecks, and disposal of chemicals, disused or discarded munitions and other matters contribute to marine pollution. Importantly, while marine pollution may be localized, certain pollutants such as Mercury (Hg), POPs, plastics, and same radionuclides have the potential to be transported globally, accumulating in areas far distant from the original source.

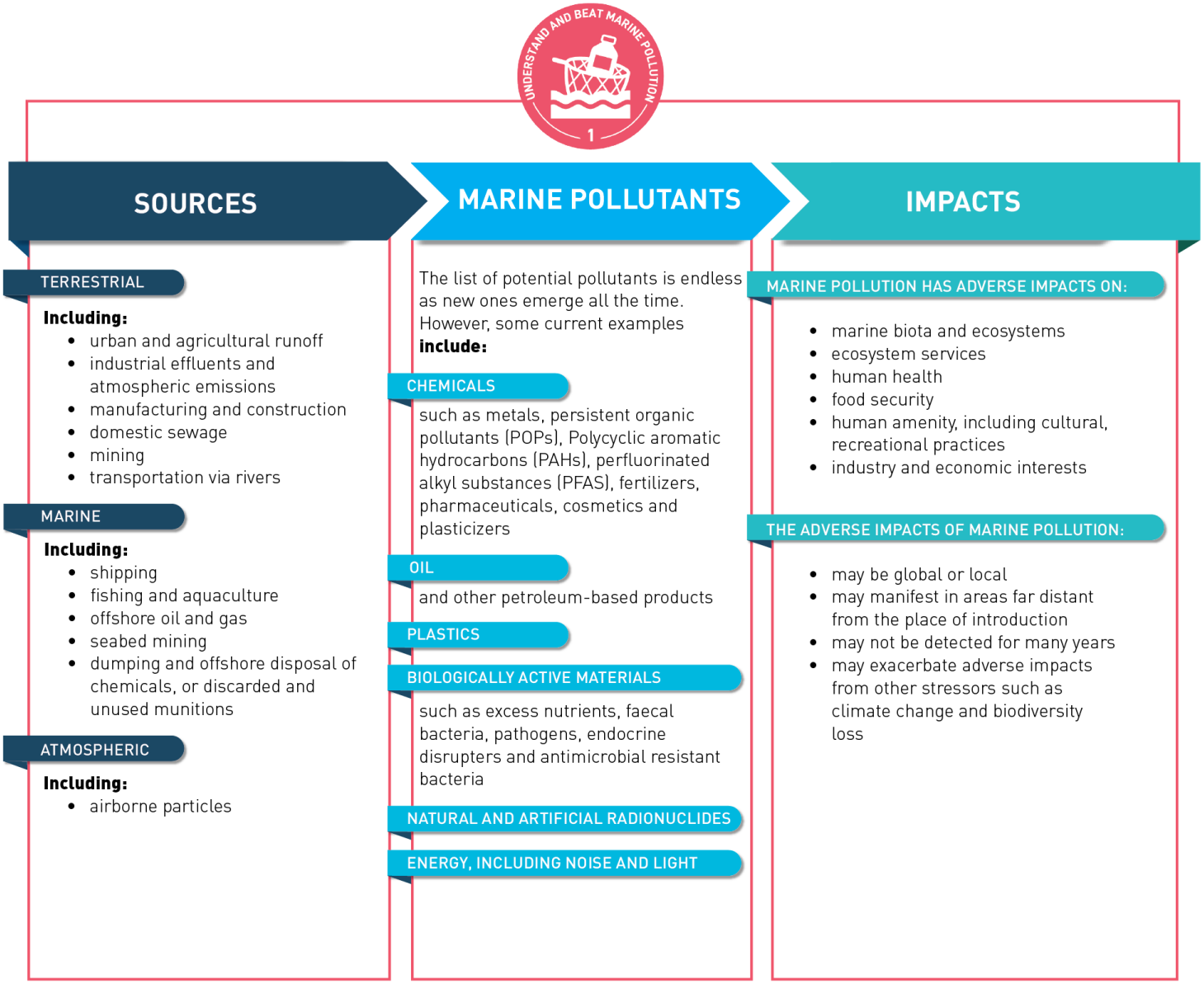

Figure 1. *Sources and impacts of marine pollution*

Currently, scientific knowledge of the sources and impacts of pollution on the marine environment is limited (WOAII 2021; UNESCO-IOC State of the Ocean, 2022). For deep ocean areas, in particular, our understanding of marine pollution is almost non-existent. Knowledge of marine pollution is primarily focused on coastal marine areas in developed countries (Global North) (Hatje et al., 2021) and typically addresses a limited number of pollutants, such as POPs, Hg, and nutrients. In addition, a lack of water and sediment quality criteria for substances of emerging concern (e.g., nanoparticles, some endocrine disruptors, and rare earth elements) impedes the assessment of their ecological and human health risks (Arienzo, et al., 2022; Piarulli et al., 2021; Neira et al., 2022; Malhotra et al., 2020). Furthermore, limited information is available regarding the additive and cumulative effects of different pollutants as well as their changing fate and impacts in the context of climate change (Hatje et al., 2022).

Compounding the limitations of our existing knowledge is a lack of harmonized protocols for studying marine pollution and marked variations in the availability of quality assurance and quality control of information for different types of pollutants (Jack et al., 2020; Schwesig et al., 2011; UNEP, 2021). Limited knowledge of baseline concentrations of pollutants and a paucity of long-term studies further hampers our ability to assess temporal trends, differentiate between natural and human-induced stressors, evaluate the long-term impacts of pollution, and assess the effectiveness of regulatory measures.

Addressing these knowledge gaps is crucial to produce knowledge, expertise, and research capabilities that enhance our understanding of marine pollution and its cumulative, long-lasting impacts on human health and ecosystem functioning (Hatje et al., 2021). Achieving this objective requires coordinated efforts, large-scale investment, enhanced availability of quality data following the FAIR (Findable, Accessible, Interoperable, and Reusability) and CARE (Collective benefit, Authority to control, Responsibility, Ethics) principles, harmonized methodologies, and the establishment of representative and sustainable long-term monitoring stations and laboratory hubs located in diverse marine environments and regions. Equally crucial is the necessity to present and communicate this knowledge in a format that is relevant, digestible, and transferable to all ocean users (Kelly et al, 2021), contributing to overall ocean literacy. Achieving this effort should be the result of a multi-stakeholder partnership aimed at bridging the science-policy gap, thereby supporting informed decision-making that ensures long-term ocean health and sustainability. This paper outlines several strategies to meet this goal.

2.2 Overview of current work in the Ocean Decade

Challenge 1, 'Understand and beat Marine Pollution', aims to understand and map land-, air-, and sea-based sources of pollutants and their potential impacts on human health and ocean ecosystems and to develop solutions to remove or mitigate them. As of November 2023, 3 Programmes, 26 Projects, and 4 Contributions (collectively 'Actions') are directly focused on addressing Challenge 1, although the issue of marine pollution may also be addressed either directly or indirectly by other Actions such as those aimed at ocean observing, prediction, and data sharing.

It is notable that Challenge 1 is significantly under-represented at both the Programme and Contribution level, with below average representation at the Project level. In addition, many of the Projects categorized under Challenge 1 exist as 'orphan' projects, which means they lack any association with a coordinated host Programme. Moreover, while Asia, Europe, and North America are represented at the Programme level, there is a dearth of Programmes in other regions and, at the Project level, major gaps exist, particularly in the Latin America and Australia/Pacific regions. Critically, there is no representation of Small Island Developing States (SIDS) in the Actions relevant to Challenge 1 to date.

Substantively, current Actions focus broadly on only three thematic areas: noise pollution, plastics, and organic pollutants. Actions dedicated to addressing noise pollution primarily focus on the creation of datasets, the advancement of knowledge about impacts of underwater noise on fish and invertebrates, and the development of innovative listening and monitoring technologies. Not addressed are issues of knowledge exchange and capacity development. Plastic pollution is addressed only at the Project level, with no specific overarching or coordinating Programme dedicated to addressing the issue. Projects within this domain focus on the development of datasets on the distribution of plastic waste, the development of greater understanding of its impacts, and the establishment of necessary infrastructure, including capacity-building initiatives to assist countries in developing management solutions for plastic waste. Despite these efforts, critical aspects such as partnerships, resource allocation, and a comprehensive approach to addressing plastic pollution at its source are not, or are only peripherally, addressed within these Projects. Similarly, while some Actions tackle issues such as freshwater pollution and organic contamination, there are no Actions explicitly focused on excess nutrients and there is little focus in these Actions on aspects such as infrastructure development, partnerships, development of best practices and resource allocation.

These gaps highlight the need for additional Actions – particularly at the comprehensive Programme level – that specifically and more cohesively address the various aspects of Challenge 1 at local, regional, and global levels, with reference to currently underrepresented geographical regions, marine-dependent populations and Indigenous communities. Furthermore, the current fragmented, uncoordinated, and insufficient representation of marine pollution issues within the Decade Actions underscores the urgent need for a Decade Coordinating Centre. This centre would serve as a central coordinating mechanism for existing and future Decade Actions aimed at analyzing and addressing marine pollution in its diverse forms, extending well beyond the current limited focus.

2.3 Importance and relevance of the Challenge for sustainable development

To ensure a sustainable future, we must recognize that marine pollution stands as one of the most serious threats to the ocean, both directly and as a multiplier, which reduces the resilience of marine ecosystems to respond to other threats such as climate change and biodiversity loss. Reducing and mitigating marine pollution helps safeguard marine biodiversity, global food security, natural resources, and ecosystem as well as cultural services. Achieving sustainable development requires collective and proactive actions to minimize and/or eliminate pollution sources and to mitigate its impacts on ecosystem and human health and well-being. It also requires reducing the economic impacts of marine pollution, including direct costs to industry and coastal communities and indirect costs to degraded ecosystems. As countries seek to develop and to sustainably expand their blue economies in furtherance of SDG 14 (i.e., Target 14.1 and 14.2), there is an urgent need to ensure that this 'blue acceleration' does not result in the introduction of new and different forms of pollution. Achieving this goal will require the development of integrated and coordinated cross-sectoral regulatory approaches that balance the sustainable use of the ocean with its protection (Rayfuse, Klein and Jaeckel, 2023) and the promotion of health and wellbeing (SGD 3). Such approaches must be based on scientifically sound data and a holistic understanding of the extent and impacts of marine pollution across the land-ocean continuum.

2.4 Methodology for strategic ambition setting

This White Paper was developed by gathering information from various sources, including responses to a questionnaire from members of the working group, consultations with specific

target groups (such as professional networks and UN agencies), online meetings, public webinars, a public review process, and a review of relevant scientific literature.

3. STRATEGIC AMBITION SETTING

3.1 Analysis of user needs and priorities

The science, data, and infrastructure needs and priorities of the wide range of users (Table 1) throughout the entire marine pollution value chain are formulated according to their different interests, purposes, roles, and mandates, and are subject to change over time. These dependencies reflect the dynamic and evolving state of ecosystems and their connection to human activities, which is the outcome of interactions across spatial and temporal scales.

Improving the quality, coverage, and availability of data regarding the state of the ocean, the pressures affecting it, their causes, and most importantly their impacts on marine ecosystems and human health and wellbeing is essential for informed governance of the marine environment and the socio-economic activities it supports. High-quality data supports science-based decisions, enabling the informed prioritization of tailored policies, managerial measures, technical solutions, as well as public and private investment decisions. Moreover, it fosters trust among users, creating entry points of cooperation or strengthening existing cooperation (Cvitanovic et al., 2021). The generation and management of reliable data and information are particularly important when applying management approaches that address the multi-layered challenges that transcend geographical scales across borders and span environmental components (i.e., biosphere, lithosphere, hydrosphere, atmosphere), economic sectors, and management sectors (Granit et al., 2017; Lucca et al., 2023). For the purposes of this paper, as shown in Table 1, a classification of users and uses of data, can guide efforts to define needs in terms of knowledge, as well as the means to acquire data and manage them.

The challenge now is to fill the knowledge gaps and to quantify the extent of impacts of marine pollution on human and ecosystem health via multi-stakeholder partnerships and knowledge sharing to provide a sound knowledge base from which effective and suitable preventive and mitigative measures can be best designed and implemented for the benefit of all users.

3.2 Definition of the strategic ambition for the Challenge

Our strategic ambition is to generate scientifically sound data to allow a holistic understanding of the extent and impact of pollution across the land-ocean continuum. This ambition aims to support the achievement of a cleaner and healthier ocean, where all ecosystems and their inhabitants thrive free from the impacts of marine pollution, allowing for their full functioning and service provision.

To achieve a clear and cohesive understanding of marine pollution and its implications for both human and ocean health we must forge connections among scientists, the private sector, the broader civil society, indigenous people and traditional communities, the general public, and governmental agencies/policymakers. A key aspect of this effort involves leveraging the involvement of all users and amplifying the voices of coastal communities, marine-dependent populations, and Indigenous communities, who are often overlooked but who are the most affected by marine pollution. Capacity building and the development of easily accessible databases and summary reports are imperative for efficient sharing of information and informed decision-making in our pursuit of combating marine pollution. Access to and transfer of technologies, particularly to those most affected, will also be key to overcoming the marine pollution challenges. Collaboratively, we must actively seek funding to address the existing knowledge and data gaps that currently impede informed decision-making.

Table 1. *Summary of data users, their data use, and the need for engagement in data generation and information sharing.*

DATA USERS	DATA USE AND KNOWLEDGE GENERATION	NEED FOR ENGAGEMENT IN DATA GENERATION AND SHARING
Scientific community	Working to enhance our understanding and generate knowledge on pollution sources, biogeochemical cycling, and impacts on ecosystems, human health, and socio-economic issues related to marine pollution, including economic impacts.	Knowledge generated should be used to inform the management of ecosystems across the land-ocean continuum (i.e., freshwater, brackish, and marine ecosystems).
Government agencies	At local, regional, national, and international levels, need to collaborate with scientists to assess the impact of pollution along the land-ocean continuum, develop policies, legislation and management plans, and implement/enforce compliance.	Instruments developed by government agencies may focus on pollution prevention and control or on the management of the environmental components affected by pollution.
Private sector	Should promote sustainability of its business by ensuring compliance with regulations and implementing measures throughout its supply chains to reduce its environmental footprint.	This approach includes rigorous environmental impact assessments of planned blue economy operations and the disclosure, by businesses and investors, of their operations' impact on the environment. This necessitates independently verified and detailed data about the impact of individual businesses, industry sectors, and investment portfolios on marine pollution control and mitigation.
Civil society	Needs to better understand the causes and effects of pollution.	This will allow civil society to effectively contribute to the dialogue for sound governance of the marine environment, enabling transparency, awareness, and action.
Indigenous people and traditional communities	Have marine ecosystems as a central component of their culture, tradition, food, and livelihoods.	Their knowledge needs to be integrated within resource management, environmental conservation strategies and mitigation of marine pollution.
General public	Must raise awareness of the sources and effects of pollution on human and environmental health.	This approach involves making informed consumption choices and advocating for, as well as adopting, pollution reduction measures.

The crux of the challenge, both up to and beyond 2030, involves decreasing the release of pollutants into the marine environment with a view to controlling, mitigating, and ultimately preventing marine pollution. This goal necessitates prioritizing the study of the most impactful current and emerging pollutants, understudied ecosystems, as well as anthropogenic activities (e.g., deep sea mining), the adverse effects of which are not yet fully understood.

To accomplish this, it is crucial to establish baseline datasets and conduct long-term studies that enable the continuous monitoring of ocean health and the impacts of marine pollution. Our **first priority** is therefore to

address data gaps related to the sources and impacts of priority pollutants (e.g., those found in high concentrations, or with high toxicity, or with known adverse effects on biota or human health, such as POPs, PFAAs, and Hg), as well as the most heavily contaminated areas globally. Our **second priority** is to implement representative sentinel stations worldwide for long-term studies that enable the evaluation of temporal trends and the effectiveness of control and remediation actions. Our **third priority** is to compile existing and new data into standardized and interoperable regional and global databases, based on common best practices for data collection, management, and dissemination that are freely available and accessible, facilitating the sharing and comparing of information and supporting better decision-making. Our **fourth priority** should be capacity building to help bridge the data gap between the Global North and the Global South, fostering the development and sharing of knowledge and technological solutions to measure and mitigate marine pollution impacts. These priorities are summarized in the Figure 2 and described in more detail below.

3.2.1 Priority datasets

To tackle marine pollution, it is essential to map and leverage existing data, while generating new knowledge on pollutant distribution, cycling, and their impacts on ecosystems and human health. Existing datasets are scattered across various platforms, making data mapping complex due to varying methodologies, metadata standards, and quality control protocols, among other factors. Additionally, privacy rights complicate the findability and sharing of data among stakeholders, especially when it comes to industry data. This issue presents a significant barrier to collaboration and knowledge sharing, hindering efforts to address marine pollution comprehensively. Acknowledging and recognizing the existing datasets can prevent redundancy and duplication and streamline priorities. The following three-step roadmap highlights the priority datasets necessary to address Challenge 1:

- *Prioritization of areas, pressures, and pollutants.* Pollution affects almost all environments to varying degrees, necessitating prioritization in terms of the types of pollutants, sources, anthropogenic pressures, and regions to be monitored. Priority should be given to monitoring, reporting, sharing information, and mitigating well-known pollutants that can harm wildlife, ecosystem services, threaten food security and human health. Examples include POPs, PFAAs, and Hg, which are already partially regulated by conventions and treaties and/or are under discussion. Additionally, focus should be placed on point-source pressures, such as river mouths, fishing and aquaculture activities, coastal and offshore infrastructure (e.g., harbors, offshore wind farms), as well as resource extraction (e.g., seabed mining), which often negatively alter ecosystems and may be sources of pollution. Focusing on heavily polluted coastal areas, particularly those with marine resource dependent and Indigenous communities, is imperative. Furthermore, attention must be directed towards emerging pollutants and pressures (e.g., seabed mining and geoengineering solutions) detected in marine environments even though their impacts are not yet understood. Historically neglected regions, many of which are in the Global South, must be monitored. Finally, expanding research and monitoring of pollutants and pressures in the open and deep ocean is essential.

Figure 2. *The six pillars of the White Paper strategic ambition proposed to understand and beat marine pollution.*

- *Long-term time series datasets.* Long-term datasets enable the identification of baseline conditions and temporal trends, helping to disentangle natural variability from anthropogenic change. Additionally, they allow the evaluation of the effectiveness of regulatory measures. Long-term monitoring is thus crucial for making meaningful global comparisons, for democratizing infrastructure access, and for assessing pollutant fluxes over time. Such monitoring will help to reveal the global pollution status, identify pollution hotspots and pollutants of concern, and help to develop effective control and mitigation strategies. To expand databases, the establishment of physical infrastructure and capabilities to develop long-term monitoring data in strategically positioned sentinel stations around the world will be critical (see Infrastructure requirements in section. 3.2.3 below). This global long-term monitoring initiative should mobilize researchers worldwide to study and monitor marine pollution using standardized methodologies and best available practices. the distribution of elements and isotopes in the marine environment over extended periods.
- *Global, regional, and national databases.* Coordinated and integrated databases housing datasets for priority pollutants, including those already affecting human health and ecosystems, as well as emerging pollutants, should be established at national, regional, and global levels. These databases will serve as a valuable resource for scientists, environmental authorities, consultants, and any other interested users to enable informed decision making and prioritization of mitigation measures. These databases should adhere to the FAIR and CARE principles and ensure data consistency and comparability by following harmonized methodologies based on common best practices for sample collection, analysis, quality control, data storage, data management, and data reporting and sharing. The UN endorsed Programme on Ocean Practices for the Decade, facilitated by the Ocean Best Practices System (OBPS), could significantly help with the efforts of harmonization of databases and associated metadata.

3.2.2 Knowledge generation and sharing

To gain a comprehensive understanding of marine pollution, its impacts, and the necessary steps to mitigate and manage it effectively, the following issues need to be addressed:

- *Methodological improvements.* High-quality data is paramount for enhancing the development and application of predictive models to better understand and anticipate pollutants behavior and impacts. To reduce methodological biases, and ensure reproducibility, accuracy, and precision to address environmental and societal challenges, laboratories should follow strict quality control protocols. Laboratories are encouraged to report data on certified reference materials or consensus intercalibration samples and to participate in proficiency tests. In addition, there is a need to lower the analytical limits of detection of pollutants and to integrate field and laboratory experiments at various spatial and temporal scales, considering the co-occurrence of multiple pollutants and the emerging effects of climate change on marine pollutants.
- *Holistic approach.* The complex interrelationships between biotic and abiotic systems across the land-ocean continuum requires the use of holistic approaches to the understanding and assessment of pollutant sources and pathways, most of which are land-based, as well as to the evaluation, reduction, and mitigation of pollutant impacts. These approaches should encompass human and ecosystem health, as well as ecosystem services and functions within

their respective social and environmental contexts.

- *Data sharing*. To enable informed decisions and prioritize mitigation measures, it is essential to leverage marine pollution data and ensure free and easy access to quality information. To enhance the comprehensibility of marine pollution issues for policymakers, private sectors, civil society, indigenous and traditional communities, and the general public, information derived from marine pollution monitoring, modelling, and mitigation efforts should be consolidated in regional, national, and global synthesis reports, as well as in easily accessible online visual resources (e.g., IPCC regional and sectorial fact sheets). An Ocean Literacy strategy focused on marine pollution should be developed locally, considering relevant contexts and realities (e.g., Ocean Data Information System (ODIS) and/or Ocean Literacy Portal of UNESCO). Citizen science activities, diverse visual products, and media should be developed and utilized to communicate the lessons learned from monitoring and mitigating marine pollution, while engaging the public in addressing this environmental challenge.

3.2.3 Infrastructure requirements

Establishing adequate infrastructure is essential for monitoring marine pollution and for data-knowledge generation and sharing. The unequal distribution of ocean monitoring infrastructure leads to uneven geographical data collection and knowledge gaps (Tolochko and Vadrot, 2021; Bax et al., 2018; Hatje et al., 2021).

To expand datasets, the establishment of long-term ocean monitoring sentinel stations, akin to the Mauna Loa station for atmospheric CO_2 measurements (known as the 'Keeling Curve' (Keeling et al., 2001; Keeling and Keeling, 2017)) is of paramount importance. Sentinel stations are needed across all oceans, spanning all latitudes and ecosystems. These sentinel stations should adopt harmonized methodologies and be strategically located in representative areas to form a comprehensive monitoring network that can monitor the global extent of marine pollution, encompassing its wide regional variability (Cooper et al., 2023), from the most pristine to the most heavily polluted areas. As a starting point, it would be desirable to establish collaborations with already existing long-term monitoring stations such as the Bermuda Atlantic Time-series Study (BATS). The already demonstrated 40 years of observations in BATS show, for instance, continuous trends of surface water warning, increase in salinity, loss of dissolved oxygen and ocean acidification effects (Bates and Johnson, 2023). It would be advisable to also include the systematic monitoring of marine pollutants at BATS and other long-term monitoring stations. Regional Sea Conventions, alongside the Basel, Rotterdam, Stockholm, and Minamata conventions, can play a crucial role in supporting and coordinating the operation of these stations, which should be coordinated by an inter-regional multi-stakeholder committee. The establishment of regional laboratory hubs, observatories, and platforms is also pivotal for understanding and mitigating marine pollution. These facilities should provide the necessary infrastructure and skilled teams to promote training, facilitate data generation, management, and sharing of regional databases on integrated platforms while upholding the FAIR and CARE principles. This infrastructure should be modelled on successful program-based initiatives, such as GO-SHIP, GEOTRACES (Cutter et al., 2017), the IAEA-Technical Cooperation Program, and initiatives established under the Regional Seas conventions, among others. Consideration should also be given to establishing regional and global infrastructure, including partnerships and funding mechanisms that can be rapidly mobilized in the event of accidental pollution incidents, such as oil spills or radioactive releases.

Infrastructure for a global, proactive, and publicly available database and data archiving system is necessary to increase transparency and knowledge sharing, particularly where

harmonized sampling and analytical methods have been used. Funding will be necessary to establish the database infrastructure compatible with the Global Information System (GIS) and for its maintenance. This infrastructure will facilitate the automated creation of maps for global pollution monitoring data with minimal effort in the future. The responsibility for and coordination of such database infrastructure should reside within the UN system with the UNESCO-IOC, possibly through the International Oceanographic Data and Information Exchange (IODE).

3.2.4 Partnerships and resources

The complexity and transboundary nature of marine pollution necessitate the development of partnerships on a range from local, national, and regional, to international scales (Polejack, 2021). These collaborations should strategically leverage resources and expertise, drawing upon and updating existing national, regional, and international strategies and action plans. Decade Collaboration Centres as well as organizations and institutions such as UNESCO-IOC and the UNEP Regional Seas Programme could play a facilitative role in maintaining continuous communication among diverse stakeholders and promoting the application of collected data.

To understand and beat marine pollution effectively it is essential to co-design ocean observing and pollution monitoring networks in partnership with a diverse range of users, including scientists, governments, private sectors, civil society, Indigenous, traditional, and marine resource dependent communities and the general public (Bax et al., 2018). This collaborative effort must aim to educate, instil ownership, and trust, and enhance public participation to foster understanding of the impacts and solutions for reducing and mitigating marine pollution. In some instances, coastal, Indigenous, and marine resource-dependent communities are ideally positioned to observe coastlines and ecosystems, alert authorities to pollution impacts, engage with local decision makers, and contribute to generating knowledge and data tailored for effective pollution mitigation.

To ensure the inclusion of local perspectives, needs, and priorities in the evaluation and mitigation of pollution, it is necessary to use existing bodies and institutions at the regional level, in addition to national or international ones. Strategic partnerships, both at the national and international levels, should be sought to leverage financial mechanisms and expertise. This approach includes the establishment of sustainable funding systems to address marine pollution issues, drawing on resources from entities such as the United Nations (e.g., Global Environmental Facility (GEF) and Green Climate Fund (GCF)), the private sector, and philanthropy. Furthermore, the formation of multilateral donor partnerships is essential for comprehensive and effective solutions.

3.2.5 Capacity development and exchange needs

The key principles for the capacity development component of Challenge 1 are engagement, justice, and co-design (Bennett, 2018; Norström, et al., 2020). Two important aspects should be highlighted within capacity development: the disparities in capacities between the Global South and the Global North, and the widespread lack of participation by local communities in data generation and sharing. Consequently, there is a need to foster engagement with coastal, Indigenous, and marine resource-dependent communities, with a specific focus on involving scientists and community members from Global South countries, Least Developed Countries, and SIDS in research activities and decision-making processes.

A just capacity development component acknowledges and respects the unique needs of each community, understands their perspectives, and seeks to address the knowledge gaps identified not only by scientists, but also by the communities themselves. Strategies and joint action plans should align with user needs, benefiting those

reliant on the ocean (Harden-Davies, 2016; Harden-Davies et al., 2022).

Top priorities for training and exchange programs should focus on disseminating harmonized methodologies, including protocols, for data consistency, offering comprehensive training covering environmental sampling, pollutant biogeochemistry, and fostering collaboration between developed and developing nations for pollution measurement, remediation, and mitigation.

International scientific cooperation and technology transfer are pivotal for efficient capacity development. Ocean science diplomacy can bridge policymakers and researchers, creating evidence-based international regulations on marine pollution (Polejack, 2021).

The aim of this capacity development framework is to bridge user gaps and promote successful pollution control stories and ecosystem recoveries, prioritizing society's involvement. Engaging policymakers, early career ocean professionals, youth, and citizen science initiative aligns with Ocean Literacy principles and aims to include marine pollution topics in school curricula. Initiatives like the Blue Schools (Costa et al., 2021), Ocean Teacher Global Academy (Claudet, et al., 2019), and World Ocean Day (https://worldoceanday.school/resources-2020/) further this goal, sharing best practices and promoting technology transfer among countries.

3.2.6 Technology and innovation solutions

To bridge global marine pollution knowledge gaps, a range of innovative technological and practical solutions are essential, including:

- *Autonomous monitoring systems:* Develop cost effective, reliable, globally deployable techniques (e.g., sensors) for fast, accurate, preferably real time, and affordable water quality and pollutant assessments (see, e.g., Balakrishnan Nair et al., 2024). Encourage citizen science participation in their maintenance and deployment.
- *Analytical techniques*: Scale up mass spectrometry, nuclear, isotopic, and emerging technologies to trace pollutant sources, distribution, and transfers across food webs, including humans.
- Widespread *wastewater treatment*: Create cost-effective and efficient systems to prevent pollutants from entering oceans.
- *Sustainable practices*: Innovate sustainable practices within industries like farming, fishing, shipping, terrestrial and deep-sea mining, and oil and gas industries to minimize their impact on marine environments.
- *Clearing-house mechanism:* Implement a clearing house mechanism, i.e., a network of parties and partners working together, for the transfer of proven and mature marine technology specifically focused on addressing pollution (see, e.g., UNESCO-IOC, 2005; Polejack and Coelho, 2021).
- *Innovative education tools*: Use narrative storytelling, games/Apps, technology-driven awareness campaigns, and platforms like UNEP's World Environment Situation Room (WESR) to raise awareness and influence positive behavioral changes in communities, policymakers, and industries.

3.3 Integration, synergies and interdependencies with other Challenges

Reducing, preventing, and mitigating marine pollution requires a holistic approach to ocean management which considers the full range of complex interrelationships between biotic and abiotic systems across the land-ocean continuum. This approach is mirrored in the interdependency between several, if not all, of the Ocean Decade Challenges.

Achieving the objectives of Challenge 2, 'Protect and Restore Ecosystems and Biodiversity' and of Challenge 3 'Sustainably Feed the Global Population' is not possible

without achieving the objectives of Challenge 1. Similarly, the objectives of Challenge 4, 'Develop a Sustainable and Equitable Ocean Economy' and Challenge 5, 'Unlock Ocean Based Solutions to Climate Change' must only be achieved in a manner that is consistent with the goals of Challenge 1.

Particular synergies exist with Challenge 7, 'Expand the Global Ocean Observing System' and Challenge 8, 'Create a Digital Representation of the Ocean', the achievement of both of which will be important to the achievement of Challenge 1. Challenge 10 'Change Humanity's Relationship with the Ocean' which deals with the concept of Ocean Literacy is key to helping raise awareness of the marine pollution issue and contributing to fostering positive behavioral changes within communities, policymakers, and industries.

Finally, capacity development and equitable access to data, information and technology, the objective of Challenge 9, 'Skills, Knowledge and Technology for All', is of central importance to addressing Challenge 1. Coordination of and between all these Challenges will be critical to ensuring the necessary tools, infrastructure and services are in place to deliver the objectives of Challenge 1.

4. KEY MILESTONES AND INDICATORS TO MEASURE PROGRESS AND SUCCESS

The overarching objective of Challenge 1 is to generate scientifically sound data to allow a holistic understanding of the extent and impact of pollution across the land-ocean continuum with a view to laying the groundwork for the future reduction of marine pollution to levels that do not jeopardize human health or disrupt ecosystem services. Looking beyond 2030, the ultimate objective is to maintain pollutant concentrations near background levels for naturally occurring hazardous substances and close to zero for human-made hazardous substances.

The key milestones and indicators that will be used to measure the fulfilment of our strategic ambition, summarized in Figure 3 below, include:

4.1 Societal and Environmental Impact

This milestone is aimed at improving the health of marine ecosystems affected by pollution, including ecosystem services, functions, biodiversity, and interdependencies with climate change, reducing the impacts of marine pollution on human health, and reducing the vulnerability of coastal communities and ecosystems to marine pollution and economic impacts. Key indicators are:

- By 2026 - The scientific community, in collaboration with marine-dependent and local communities and under the coordination of UN entities, supported by the Decade Collaborative Centre on Marine Pollution will define a priority pollutants list and the scope of a comprehensive data and knowledge gap analysis.
- By 2028 - Completion of the analysis of data and knowledge gaps and development of strategies for closing them based on the review of the literature and available databases by the scientific community coordinated by UNESCO-IOC.
- By 2029 - Completion of Decade Actions involving the scientific community together with UN entities and governmental agencies that identify key pollutant threshold risks, for different environmental compartments, focusing on impact, to assess global ocean health.
- By 2030 - Completion of Decade Actions involving the scientific and academic communities, coordinated by UN entities and governmental agencies, for comprehensive assessments of the interplay between pollutants and climate change, examining combined impacts on marine ecosystems and biodiversity.
- By 2030 - Development, through targeted Decade Actions, of harmonized protocols for sound scientific decision-making regarding marine pollution by policymakers, local communities, academia, and NGOs.

4.2 Enhanced Ocean Data Accessibility and Availability

This milestone will be achieved by ensuring the increased availability and accessibility of ocean data relating to marine pollution, including the streamlining of data-sharing platforms, standardized data formats, and open access policies. Key indicators are:

- By 2025 - With the help of the Decade Collaborative Centre on Marine Pollution, establishment of a network of scientists to discuss and construct harmonized protocols for robust, rigorous, and scientifically sound monitoring and data sharing of marine pollutants, to be coordinated by UNESCO-IOC.
- By 2026 - Establishment of an inter-regional multi-stakeholder committee to define specifications and operational conditions for the number, location, establishment, and operation and maintenance of sentinel monitoring stations, including the definition of the

priority pollutants, along with terms of reference for ongoing monitoring to ensure implementation of these specifications and operational conditions.

- By 2027 - Call by UNESCO-IOC for institutions interested in becoming a regional laboratory hub to support sentinel stations.
- By 2028 - full and visible participation of the Ocean Decade in the OceanObs'29 Conference to be hosted in China in 2029, to ensure the seamless integration of marine pollution, biology, and ecosystem operations, research, and applications into the framework for ocean observing.
- By 2030 - Commencement of implementation of long-term monitoring programs in sentinel stations by UNESCO-IOC.
- By 2030 - Construction of consolidated regional and global databases of marine pollution to be hosted by an UN agency.

4.3 Building Capacity for Understanding and Beating Marine Pollution

This milestone is aimed at the development of increased capacity of individuals, institutions, and communities to effectively address the causes and impacts of marine pollution, and to monitor and minimize its impacts in both the short term and for the long term. Key indicators are:

- By 2026 - Design training sessions to implement harmonized protocols for the production, collection, analysis, interpretation, dissemination, and management of marine pollution data. These sessions will ensure completeness, timeliness, interoperability, and quality of data generation, dissemination and management by scientists and other stakeholders.
- By 2026 - Implement Decade Actions involving academic communities, local communities, NGOs, UN entities, and resource providers to deliver training programs focused on disseminating harmonized protocols. These programs will support the sound generation, management, interoperability and sharing of data and knowledge, with particular emphasis on developing and least developed countries.
- By 2030 - Member states, resource providers, resources managers, UN entities, academia, Regional Seas conventions and other regional environmental bodies should establish a network of regional marine pollution laboratory hubs for monitoring, training, and data sharing. This network should focus on addressing the geographical gap in the Global South (e.g., data and expertise), particularly in developing and least developed countries.

4.4 Advancement in Ocean Technology and Innovation

This milestone requires increased advances in ocean technology, innovation, and infrastructure to support research relating to marine pollution and its control, prevention, and mitigation. Key indicators are:

- By 2026 - Completion of Decade Actions involving scientists, academia, NGOs, the private sector, resource managers, and providers focusing on the analysis of technology and innovation gaps for monitoring pollutants.
- By 2027 - Production of lists of recommended approaches, including instrumentation and software for screening and target pollution measurements and/or analysis.
- By 2028 - Completion of a wide range of Decade Actions, predominantly at the project level, involving academia, NGOs, the private sector, local communities, and resource providers, specifically targeted at the ongoing development of robust, innovative, and cost-effective technologies and devices for screening and monitoring pollution across the land-ocean

continuum, including the development of associate harmonized protocols.

- By 2030 - Completion of Decade Actions involving academia, local communities, governmental, and intergovernmental agencies aimed at the implementation and global adoption of robust, innovative, and cost-effective technologies for monitoring pollution across the land-ocean continuum.
- By 2030 - Completion of Decade Actions and securing ongoing support levels by the private sector, resource managers, and resource providers involving the development of new, cost-effective technologies to mitigate marine pollution at local, regional, and global levels.

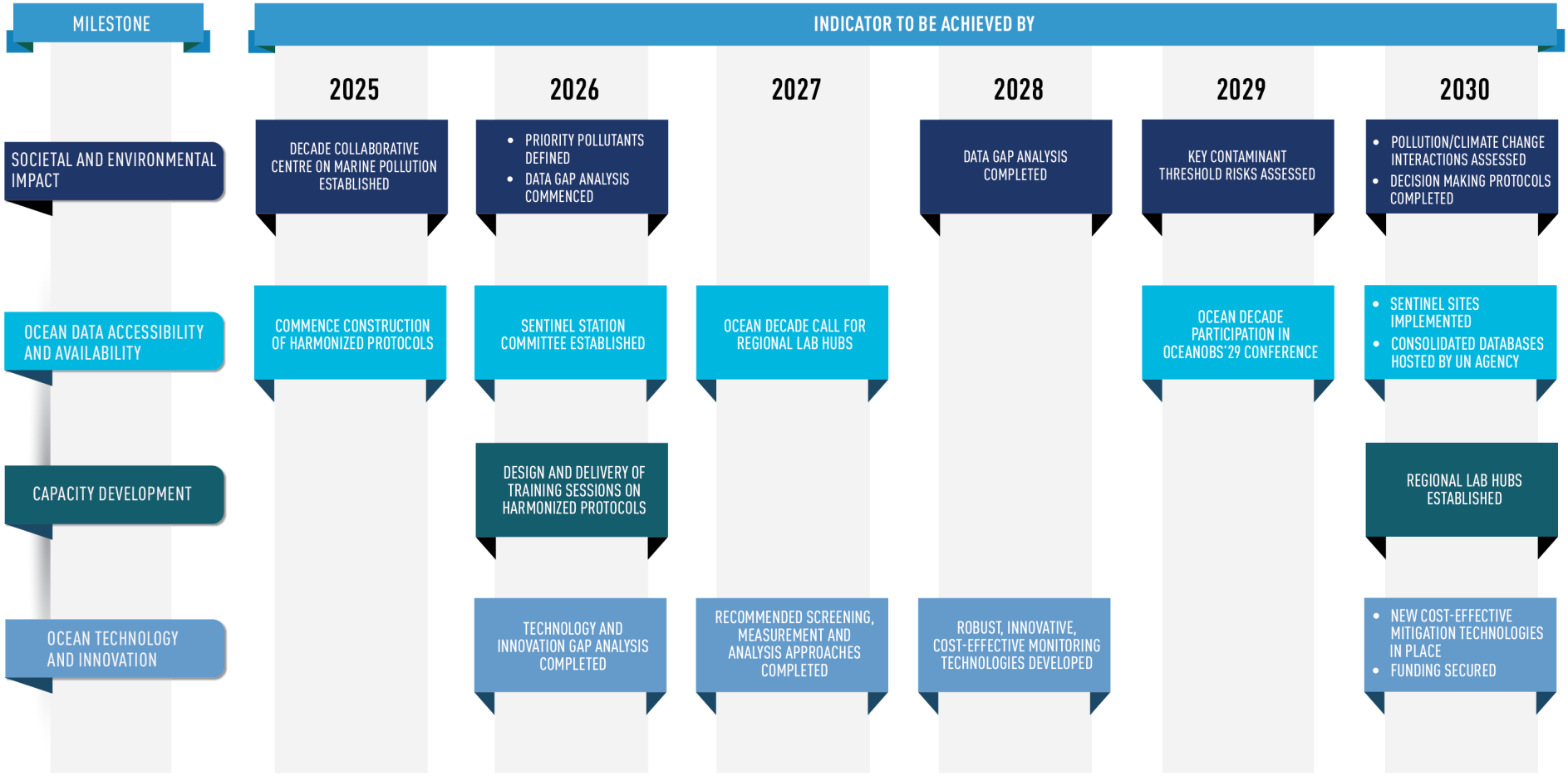

Figure 3. Key Milestones and Indicators to be achieved by 2030.

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United Nations Decade of Ocean Science for Sustainable Development (2021-2030)

Proclaimed in 2017 by the United Nations General Assembly, the UN Decade of Ocean Science for Sustainable Development(2021-2030), provides a convening framework to develop the scientific knowledge and partnerships needed to catalyse transformative ocean science solutions for sustainable development, connecting people and our ocean. The Ocean Decade is coordinated by UNESCO's Intergovernmental Oceanographic Commission (IOC).

Established during the Preparatory Phase and to continue throughout implementation until 2030, the IOC's Ocean Decade Series will provide key documentation about this global initiative and aims to serve as a primary resource for stakeholders seeking to consult,monitor and assess progress towards thevision and mission of the Ocean Decade.

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