Technology Foresight

Observing the Future

Horizon scanning for emerging technologies and breakthrough innovations in the field of ocean observation

2026

HIGHLIGHTS

▶ This **Horizon Scanning** exercise was developed to support **European Innovation Council** strategic intelligence in the field of **ocean observation,** as well as to provide inputs to other European Commission services such as DG MARE and DG RTD. **Horizon Scanning is a qualitative foresight method**, aiming at the early discovery of developments before their potential is widely recognised.

▶ **Eight observation technologies** were prioritised by workshop participants: autonomous eDNA and eRNA samplers; lab-on-chip systems; cost-effective and modular sensors; data fusion in Earth observation and *in-situ*; distributed acoustic sensing; AI-enhanced passive acoustic sensing; deep learning-enabled imaging; flow cytometry and particle-based high-frequency observations of plankton.

▶ Additionally, **four enabling technological and innovation fields** were pointed out as key for the advancement of this field: expanding *in-situ* observation; data interoperability and integration; autonomous surface and underwater vehicles; and AI.

▶ **Several contextual factors** that shape the development of ocean observation were highlighted across social, technological, economic, environmental and political/regulatory domains. Some of these include: data standards and taxonomic expertise; the tension between budget constraints and rising monitoring demands; accelerating environmental change requiring real-time detection; and geopolitical dynamics affecting international cooperation and dual-use technologies.

▶ **Conclusions point out that the future of ocean observation** will be shaped by technology convergence: integrated systems combining diverse in-situ sensing technologies, autonomous platforms and AI-enabled data analytics. These are essential to deliver continuous, cost-effective and trusted observations capable of supporting science, policy and governance in an increasingly complex and dynamic ocean environment.

'How inappropriate to call this planet Earth when it is quite clearly Ocean'

Arthur C. Clarke

Introduction

Project context

This document reports on the conclusions of a Horizon Scanning exercise developed in the context of project FUTURINNOV (FUTURe-oriented identification and assessment of emerging technologies and breakthrough INNOVation).

This project is a collaboration between the European Commission's (EC) Joint Research Centre (JRC) and the European Innovation Council (EIC), the EC's flagship program for deep tech, implemented by the European Innovation Council and SMEs Executive Agency (EISMEA).

FUTURINNOV was designed to support the EIC in building strategic intelligence capacity through foresight and other anticipatory approaches. It supports activities focused on funding targets, programme design, policy feedback, and institutional governance.

The outcomes of this exercise may be used to inform future funding topics for EIC Challenges and other EC calls. They can also provide input for EIC and EC reports, as well as supporting other EU policy-making initiatives.

Methodology

Horizon Scanning is a qualitative foresight method which is aimed at the early discovery of developments not yet on the radar of some experts, decision makers, or the general public, and whose potential is not yet widely recognised. It is not a predictive tool, rather it encourages the exploration of novelties that offer opportunities and challenges in the medium or long-term. [1, 2, 3]

FUTURINNOV includes a series of thematic workshops that follow a tailor-made approach to this methodology. This approach uses a participatory detection, clustering, and sense-making process for signals, trends and contextual factors related to emerging technologies and breakthrough innovations. Each workshop is dedicated to a specific EIC Programme Manager's portfolio, or a domain deemed of interest by the EIC.

Trends and signals[1] are captured through a series of participatory exercises preceded by qualitative desk research, as well as data and text mining. They originate from a diversity of sources, ranging from scientific publications, patents and previously funded projects to institutional websites, news, online articles and other media.

During each workshop, through a specific methodology composed of several analytical and selection steps (by voting), participants converge on a priority list of topics.[2]

The criteria for this selection include relevance to the exercise's scope, potential impact and overall novelty across all technology readiness levels. The final topics include technologies and innovations, as well as relevant contextual factors for their development and uptake.

This report refers to a specific workshop held online on 12 November 2025 with a focus on emerging technologies and breakthrough innovations in the field of ocean observation.

For this specific workshop, including the phases of scope definition and selection of signals, the JRC and EISMEA established a partnership with other European Commission services such as the Directorate-General for Maritime Affairs and Fisheries (DG MARE) and the Directorate-General for Research and Innovation (DG RTD), namely the units

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[1] The understanding of what constitutes a signal or a trend may vary [90, 91]. As it is not yet consensual, for the purposes of this project both are relevant and understood as tangible manifestations of novelty in science, technology, innovation, markets, media, and other fields. They can cover different maturity levels from basic research to commercial readiness. Although often used interchangeably, a signal is less consolidated than a trend.

[2] For this exercise, the JRC and the EIC compiled and assessed a longlist of trends and signals for their relevance to the workshop's scope and objectives. This list was then refined with the support of DG RTD and DG MARE to a shortlist of 175 items and shared with participants ahead of the event. From this shortlist, the JRC extracted specific technologies and innovations (often more than one per signal), removed repetitions and overlaps, and organised them into two clusters: A. core observation technologies and B. enabling technologies. These two curated lists formed the basis for the workshop discussions. Participants reviewed the lists in separate steps, added additional relevant or previously overlooked topics, grouped and linked related issues, and ultimately converged on a final set of topics for both clusters, summarised in this report. The final topics are presented together with the bibliographic references of the signals collected before the workshop, supplemented where necessary with additional desk research carried out after the workshop.

working on the Blue Economy domain.

The workshop was held with a group of selected experts from academia, research and technology, business, consultancy and policy-making organisations, including those DGs mentioned above. This diversity of institutional backgrounds, as well as various fields of specific expertise, was key to bringing different perspectives to the conversation. The resulting collective intelligence helped to build significant insights around the emerging technology landscape in the field of ocean observation.

Scope and policy context

Ocean observation refers to the monitoring and measurement of the ocean's physical, chemical, biological, and geological properties over time and space. It is essential for understanding and protecting ocean ecosystems and for informing environmental and economic policies. Data is collected today by different authorities for different specific purposes, including the implementation of the Green Deal [4].

The European Union (EU) has positioned ocean observation as an important field for its environmental and economic strategies, namely with the European Ocean Pact, adopted in June 2025 [5]. The pact brings together several EU policies and actions related to the ocean and creates a unified and coordinated management plan built around six priorities:

- Protecting and restoring ocean health
- Boosting the competitiveness of the EU sustainable blue economy
- Supporting coastal and island communities, and outermost regions
- Advancing ocean research, knowledge, skills and innovation
- Enhancing maritime security and defence
- Strengthening EU ocean diplomacy and international ocean governance.

Among the actions in the Pact, we can find the launch of an EU Ocean Observation Initiative, which will be underpinned by an Ocean Research and Innovation Strategy. Also, the EU is developing a European Digital Twin of the Ocean (EU DTO) by 2030 - a digital representation of the ocean and its multiple components. [5]

The EU is supporting multiple other initiatives. The EU4OceanObs is one of the main EU programmes

for coordinating ocean-observation efforts. The ongoing second phase will continue to pursue goals such as building partnerships (within the EU and internationally), enhancing observation infrastructure, improving data sharing, and increasing Europe's influence in global ocean governance. EU4OceanObs aligns EU efforts with global frameworks such as the UN Decade of Ocean Science for Sustainable Development (2021–2030), which aims at sustainable ocean science and improved forecasting, monitoring, and data utilisation. [6]

The EU also supports a diversity of open and interoperable marine data platforms, such as the Copernicus Marine Service and the European Marine Observation and Data Network (EMODnet), [7, 8] and has set up the Joint Programming Initiative (JPI) Oceans. This initiative has a role in prioritising and funding transnational research and innovation to increase the efficiency and impact for sustainable, healthy and productive seas and oceans. [9]

Finally, the EU Mission "Restore our Ocean and Waters" aims to rebuild the health of Europe's marine and freshwater systems by 2030 by restoring ecosystems and biodiversity, eliminating pollution (in line with the Zero Pollution Action Plan), and steering the blue economy towards a carbon-neutral and circular model. The EU DTO mentioned previously, will be funded through this mission. [10]

At the global level, it is worth highlighting the agreement under the United Nations convention on the law of the sea on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction (BBNJ Agreement), that entered into force in January 2026. It complements EU efforts by establishing frameworks for conservation in areas beyond national jurisdiction, emphasising biodiversity monitoring and integrated ocean governance. [11]

These multiple initiatives provide a global and an EU level policy context for this exercise. They highlight the importance of additional policy measures — including but not limited to potential EIC funding — and how they can contribute to an integrated approach. One that strengthens the EU ocean observation capacities, particularly through further development of emerging technologies and breakthrough innovations.

Figure 1 – EC President Ursula von der Leyen at the 3rd United Nations Ocean Conference (UNOC3) with presentation of EU DTO, Nice, France, 8–9 June 2025.

Source: European Commission - Audiovisual Service (audiovisual.ec.europa.eu)

Quick guide

This report is organised in 3 sections:

- trends and signals on technologies and innovations.
- contextual factors, covering drivers, enablers and barriers related to the development and uptake of those technologies and innovations.
- conclusions providing complementary insights and overarching analysis.

Trends and signals

The trends and signals presented in this section were identified by participants as the most relevant within the scope of the workshop. They are organised in two clusters:

- A. core observation technologies and innovations - solutions directly enabling in situ observation, measurement, and sensing [3].
- B. enabling technologies and innovations - solutions that support and enhance the core technologies and make possible the collection of relevant data.

This clustering reflects the methodology applied in the pre-workshop signal analysis and in the assessments conducted by participants during the online workshop. It helps distinguish between

domain-specific technologies—such as sensors, samplers and other solutions that directly support observation capacities—and technologies with cross-cutting relevance, whose enabling or convergent nature allows them to be applied across multiple fields, such as AI and autonomous vehicles.

Within each cluster, the signals were often grouped under broader topics with different levels of granularity and interconnectedness. The cluster on enabling technologies for example includes topics in a more aggregated structure, consistent with the workshop discussions. This cluster includes enablers with strong technological and innovation dimensions and is complemented by non-technological topics in the contextual factors section.

Both clusters are presented in order of decreasing priority (determined by number of votes given by the participants), with minor editorial adjustments to improve clarity and coherence.

A. Core observation technologies and innovations

A.1 Autonomous eDNA sampler

Overview and novelty

Autonomous environmental DNA (eDNA) samplers enable automated collection, filtration, and preservation of genetic material in seawater, replacing labour-intensive and ship-based sampling.

Recent systems span from compact coastal units to pressure-tolerant deep-sea samplers and can be mounted on platforms such as gliders, autonomous underwater vehicles (AUVs), Remotely Operated Vehicle (ROVs), and uncrewed surface vessels (USVs).

Their main innovations include multi-sample autonomous operation, in situ preservation, automated cleaning or sterilisation, and reduced contamination risk.

Some recent devices also link directly to microfluidic sensors (see Box 1) or full laboratory and cloud-based analysis systems, creating more reliable workflows for long duration deployments in remote

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[3] The terms sensing, measurement, and observation—often used interchangeably—refer to distinct but related concepts. Sensing denotes the physical detection of environmental phenomena by instruments; measurement translates these detections into calibrated, quantitative values; and observation integrates and interprets measurements across time and space, often in combination with models and contextual information. For clarity, this report mainly uses the term "observation."

environments.

Applications and opportunities

These technologies support a wide range of ocean-monitoring needs, such as improving taxonomy, detecting rare species, fish stock assessments, characterising microbial communities, and assessing environmental risks, pathogens, or invasive species. They are also useful for other applications, such as monitoring protected areas, offshore infrastructure, aquaculture sites, and coastal discharges.

Their ability to operate at fixed locations or as mobile payloads provides finer temporal detail and makes it possible to observe short-lived or otherwise missed biological events. They can also supply key data inputs for emerging digital twins and ecosystem models.

Challenges and future development

Remaining challenges include contamination control, power and reagent limitations, biofouling[4], method biases, and incomplete DNA libraries[5].

Improving long-term reliability, deep-water autonomy, and interoperability with existing observation systems will be essential to scale-up the use of these tools.

Sources: [12, 13, 14, 15, 16, 17, 18, 19]

Figure 2 – A biosampler installed in IRIS, an autonomous underwater vehicle (AUV) developed by INESCTEC and CIIMAR.

Source: INESC Brussels HUB

Box 1: Other molecular-level sensors

Recent advances in molecular ocean observation show a clear shift toward faster, more automated, and more targeted biosensing. The autonomous eDNA sampler presented earlier fits within this broader trend toward expanding *in-situ* molecular detection.

A. The μ-Sensor represents one part of this evolution: a micro-fluidic genosensor capable of detecting specific pathogens through their DNA signatures.

Micro-fluidic and lab-on-chip approaches (see below) are increasingly cited in marine biotechnology literature as essential for reducing sample-handling steps and enabling near-real-time detection of harmful microbes in coastal and freshwater systems.

These technologies support early-warning capabilities for *Vibrio, E. coli*, cyanobacteria, and other high-risk species, complementing broader eDNA surveys by adding species-specific and high-confidence detection.

B. At the same time, environmental RNA (eRNA) monitoring is emerging as a promising next step for biodiversity assessments. Because eRNA degrades rapidly, it provides a more immediate snapshot of living organisms compared with eDNA, which can persist for days or weeks.

This approach is increasingly recognised in genomic monitoring studies as a way to improve accuracy, reduce false positives, and support real-time ecosystem assessments, including detection of invasive species and responses to human activities.

C. A broader technological trend underpinning these developments is the incrinsing maturity of **lab-on-chip (LoC) systems** for *in-situ* chemical and molecular analysis.

By miniaturising reagent handling and optical measurement steps, LoC platforms allow

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[4] Biofouling (or biological fouling) refers to the unwanted build-up of living organisms—such as microbes, plants, algae, or small animals—on surfaces where they should not grow. This can happen on ship or submarine hulls, sensors, water systems, grates, and even in ponds or rivers. Their accumulation interferes with how these structures or devices are supposed to function and can reduce their efficiency or cause damage.

[5] DNA reference libraries improve eDNA species identification accuracy by providing more complete, correctly annotated sequence targets for matching, which reduces both false negatives (missed species) and false positives (misidentified sequences).

laboratory-grade assays—such as nutrient profiling, pH and alkalinity analysis, or targeted molecular detection—to be carried out autonomously in the water column or on platforms.

Their compact, low-power microfluidic architecture supports long-duration deployments while enabling high-frequency sampling that captures short-lived environmental changes often missed by traditional shipboard sampling.

As precision and depth capability continue to improve, LoC technologies are increasingly recognised as a key enabler for next-generation sensors. They can provide additional automation, stability, and near-real-time analytical capacity required to integrate DNA, RNA, and biochemical assays into autonomous observing platforms.

Sources: [12, 20, 21, 22, 23, 24, 25, 26, 27, 28]

A.2 Cost-effective and modular sensors

Overview and novelty

Cost-effective and modular sensors are facilitating new ways to collect ocean data at scale. The signals discussed by participants point to a shift from high-cost, specialised systems towards adaptable, standardised sensor packages that cover basic physical, chemical, and biological parameters.

Platforms such as SEAPERCH II, SCOOP and CHEMINI (see links in the bibliographic references below) illustrate this trend through plug-in modules and simple robotic add-ons that users can assemble according to local monitoring needs.

The novelty does not lie in advanced individual sensor performance, but in affordability, miniaturisation, modular design, and open data workflows. These features lower entry barriers and make ocean observation more widely accessible.

Applications and opportunities

Modular low-cost systems can support dense, local sampling across coastal and nearshore environments by allowing many small units to be deployed in parallel.

They can also enable rapid prototyping of sensing payloads, helping innovators test ideas before moving to research-grade platforms.

Their accessibility creates opportunities for ocean literacy, citizen science, school programmes, and community initiatives to contribute to environmental observations. This can increase data availability for coastal management, biodiversity assessments, and climate-related studies.

Cost reductions across the full life-cycle—not just manufacturing—further increase their suitability for long-term monitoring. In particular, solutions that reduce energy consumption, when for example combined with energy-harvesting systems, lower operational costs by decreasing maintenance and servicing needs.

Challenges and future development

Ensuring reliable data quality remains the main challenge, including calibration, stability, and consistency across large numbers of (usually) low-cost sensors.

Environmental robustness, biofouling, and limited navigation or endurance can further constrain use. Having diverse user groups also requires clear standards for metadata, data upload, and basic quality control. This is also key to enable time-series analysis and data integration across large numbers of sensors.

Future progress will depend on developing validated, standardised sensor packages, improving durability, and harmonising performance specifications. Strengthening training and support is also essential for community-generated data, so it can be trusted and integrated into wider observing systems.

Sources: [29, 30, 31, 32]

A.3 Data fusion – Earth observation and *in-situ*

Overview and novelty

Data fusion between Earth Observation (EO) *and in-situ* measurements is becoming essential for capturing fast, small-scale ocean processes, while ensuring accuracy. Examples explained below illustrate a shift toward integrated observing systems in which satellites offer the global picture and *in-situ* platforms supply the accuracy needed for interpretation and validation of data.

Workshop participants also highlighted the importance of data interoperability and integration solutions, a topic explored in more detail in the enabling technologies and innovations cluster.

Applications and opportunities

The Surface Water and Ocean Topography (SWOT) satellite maps small, short-lived ocean features that shape heat, carbon, and nutrient transport, but its observing schedule creates gaps that must be filled by in-situ instruments. Combining SWOT measurements with data from profiling floats, gliders, drifting buoys, fixed platforms, and coastal observing stations improves estimates of currents, mixing, wave energy, and heat transport—information essential for climate models, digital ocean twins, and operational forecasting.

The same applies to satellite monitoring of floating plastic, which provides broad coverage but still depends on tracking buoys or tagged objects for verification. Linking satellite imagery with floating trackers or river sensors supports the tracking of debris pathways and accumulation zones, enabling more targeted cleaning actions and better pollution control.

A data integrated approach can also strengthen EU initiatives such as the Copernicus Level-4 (L4) ocean products6, which combine satellite observations and in-situ measurements into gap-free maps of ocean conditions. Improved L4 products support more reliable early-warning services and help develop indicators relevant to ecosystem, climate, and pollution monitoring.

Challenges and future development

Differences in timing, resolution, uncertainty and data formats currently make it difficult to combine satellite and *in-situ* measurements effectively.

Detecting plastics from space remains limited by sensor sensitivity and environmental conditions such as waves and cloud cover.

Further progress requires common data standards, stronger long-term *in-situ* networks, improved automated detection methods, development of specific algorithms and robust validation frameworks to ensure that fused datasets are

trustworthy for scientific, operational, and policy uses.

Sources: [33, 34, 35, 36, 37, 38]

Figure 3 – A screenshot of the MyOcean (light) a page is dedicated to ocean data visualisation.
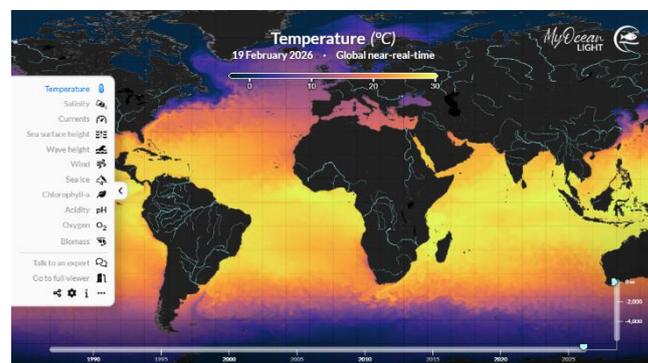
Source: Mercator Ocean International (www.mercator-ocean.eu)

A.4 Distributed acoustic sensing

Overview and novelty

Distributed acoustic sensing (DAS) is emerging as a potentially transformative approach for ocean observation. By turning existing subsea fibre-optic cables into dense acoustic arrays, DAS provides continuous measurements over tens of kilometres with fine spatial and temporal resolution.

The novelty lies in repurposing telecom infrastructure for environmental monitoring and in combining DAS with other approaches such as distributed temperature sensing (DTS).

Recent demonstrations highlight its ability to detect marine mammals, vessel activity, microseisms, ice-ocean interactions, and even real-time ocean currents during extreme weather.

Additional technologies—AI-enabled bioacoustics, passive acoustic recorders (see Box 2), and integrated non-invasive monitoring (video, acoustics, eDNA)—can extend the analytical and ecological value of DAS-based systems.

Applications and opportunities

DAS supports wide-area, persistent monitoring relevant to hazard detection (calving-related

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6 Copernicus Level-4 (L4) ocean products are gap-free, gridded datasets that combine satellite and in situ observations with advanced interpolation and data assimilation techniques. These products are central to the Copernicus Marine Environment Monitoring Service (CMEMS), supporting ocean monitoring, forecasting, and climate research by providing high-resolution, continuous fields of key ocean variables.

tsunamis[7], landslides), coastal operations (navigation and port safety), and long-term ocean and cryosphere research.

It offers a cost-effective way to large-scale acoustic observatories by using cables already on the seabed. When combined with traditional hydrophones (e.g. moored, drifting, mounted on AUVs, etc), AI sound classification, and ecological data streams, DAS can contribute to richer assessments of biodiversity, environmental impacts, and oceanographic processes.

Its capacity to operate during storms or in ice-dominated regions further strengthens operational resilience. It is also considered to be a technology with a clear dual-use potential due to its capacity to support the detection of vessels.

Challenges and future development

Limitations include dependence on cable placement (including variable coupling to the seabed), restricted sensing geometry, and large processing requirements. Progress depends on improving calibration, standardising metadata, automated detection and inversion methods, and long-term multi-site trials.

Integrating DAS outputs with complementary acoustic tools and biological monitoring systems will also be key to delivering relevant insights.

Sources: [39, 40, 41, 42, 43, 44, 45, 46, 47, 48]

Figure 4 – A conceptual image showing fibre optic cables running along the ocean floor.

Source: Adobe Stock (stock.adobe.com)

Box 2: AI-enhanced passive acoustic sensing

Alongside advances in distributed acoustic sensing, workshop participants also highlighted new AI-enhanced passive acoustic systems.

These are moving from simple detection of marine sounds to producing insights related to biological data and near-real-time.

Deep-learning models can now extract species-specific call types (e.g. for whales), estimate population size, and distinguish fauna sounds from environmental noise.

Recorders activated by triggers can operate continuously and, when additionally equipped with edge-computing capacity, process data onboard, reducing the need for manual annotation and continuous external data connections.

Innovations in this area also include higher energy efficiency. One signal described a prototype that successfully demonstrated how energy harvested from underwater sound can power a tiny processor, run a lightweight neural network and transmit results via backscatter communications[8]. This opens the possibility of future sensing nodes capable of recognising animal calls without the need for batteries.

These innovations can support the protection of sensitive species, rapid checks on reef and other ecosystems' health, as well as routine monitoring of human infrastructures, such as offshore energy, and shipping traffic.

Challenges remain as models need broader local-specific training data (although convoluted neural networks can reduce this), regular calibration and stronger noise resilience. Wider deployment also requires improving robust moorings, biofouling control and standards for data sharing.

Sources : [49, 50, 51, 52, 53, 54, 55, 56]

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[7] Calving-related tsunamis are waves generated when large ice blocks break off (calve) from glaciers or ice cliffs located next to the ocean.

[8] Backscatter (or backscatter communication) refers to a communication technique in which a device does not generate its own radio signal. Instead, it modulates and reflects ("scatters back") an existing signal—for example from a nearby transmitter, reader, or ambient acoustic/electromagnetic source—to encode and send information.

A.5 Deep learning-enabled imaging flow cytometryc

In line with AI-enhanced acoustic sensors (highlighted in Box 2) participants also identified microbiome monitoring as one area where AI acts as a key enabler (see also Box 4).

This innovation uses eDNA, eRNA, Lab-on-Chip systems (see also topic A.1 and Box 1) and deep-learning imaging flow cytometry to characterise marine microbial communities in near-real time.

Cytometry is a method used to measure and analyse the physical and chemical characteristics of cells or particles. When combined with imaging, it captures detailed images of each cell, combining the speed of flow cytometry with the analytical depth of microscopy (see also Box 3 for particle-based measuring, that targets larger cells, colonies and bloom-forming species).

The novelty therefore lies in combining molecular and imaging techniques with automated *in-situ* analysis. In this way it reduces the need for extensive laboratory infrastructure and provides near-real-time and high-resolution insights into ecosystem health.

Applications and opportunities

Microbiome monitoring can be used to track pollution impacts, detect harmful algal blooms, assess antimicrobial resistance, and support aquaculture. Microbial indicators can reveal early signs of ecosystem change and, more broadly, support the management of marine protected areas, for example by helping to guide reef restoration efforts.

Portable, high-throughput systems such as this one, bear opportunities for use on autonomous platforms, improving the responsiveness and biological insights of ocean-observation networks.

Challenges and future development

Key challenges include transparent and explainable datasets, standards and protocols and ensuring accuracy in diverse conditions. Integration with existing systems requires robust Lab-on-Chip designs, and sustained calibration.

Future progress depends also on stronger local and regional reference datasets, multimodal integration

with other sensors, and further automation to make microbiome monitoring a scalable routine operation.

Sources: [57, 58, 59, 60]

Box 3: Particle-based high-frequency observations of plankton

Still at the microbial-scale (as in the previous topic) particle-based plankton sensing, differs from molecular approaches by targeting larger cells, colonies and bloom-forming species. Although it uses similar approaches (high-throughput imaging and automated classification) this technology addresses a different layer of the ecosystem, completing a continuum from microbes to plankton.

These approaches can provide more frequent and coherent measurements of plankton communities than traditional manual sampling. By capturing particle-level information at the temporal scales at which blooms develop, they reduce data gaps and improve the consistency of observations across instruments. This enables clearer tracking of plankton dynamics and offers a stronger basis for understanding pelagic (open water) ecosystems.

As a result, they enable early detection of harmful algal blooms, strengthen biodiversity assessments and provide more reliable inputs for ecosystem models and satellite validation. They are compatible with both fixed stations and autonomous platforms contributing for continuous and large-scale monitoring efforts.

Source : [61]

B. Enabling technologies and innovations

B.1 Expanding *in-situ* observation

Overview and novelty

Participants converged around the opportunity to expand *in-situ* ocean observations, particularly in coastal and near-shore environments, through Vessels of Opportunity (VoO).

The Fishing Vessel Ocean Observing Network (FVON) exemplifies a practical example of this and a shift

towards using existing maritime activity to increase measurement capacity.

Rather than relying on new fixed platforms, this model embeds cost-effective[9], modular, and standardised sensors on vessels already operating at sea.

It can turn fishing operations into continuous, fine-scale, standardised *in-situ* observation data streams, offering a scalable and community-centred way to fill data gaps.

Another *in-situ* innovation *are* non-invasive animal tagging solutions. Previous tagging technologies were often invasive, potentially altering animal behaviour. New solutions and methods, such as suction-cups, harness or dissolvable tags, are promising, particularly if cost-effective and further integrated with AI systems.

Applications and opportunities

Using fishing fleets as *in-situ* observation platforms can significantly enhance understanding of coastal dynamics, support ecosystem assessments, improve habitat and resource management, and strengthen early-warning systems.

It also promotes closer collaboration with the fishing sector, fostering shared stewardship of stock preservation and improve the trust, relevance and uptake of environmental data within coastal communities.

Because it builds on existing fleets, the approach keeps costs low while contributing valuable *in-situ* measurements. These can be in the context of local or national monitoring strategies, as well as of global systems that depend on dense coverage.

Although fishing vessels are perhaps the most recurrent example, the opportunities also include merchant, military, research vessels, and cruise liners, ferries, or even private yachts and sailing boats.

Challenges and future development

Key challenges include ensuring consistent data quality across heterogeneous vessels, maintaining simple and robust sensor packages, and integrating

data collection smoothly into routine economic activity.

Future progress will require clear standards, long-term incentives for participation, streamlined data-handling workflows, and mechanisms to ensure that these *in-situ* observations can be reliably incorporated into science and policy.

Sources: [62, 63, 64]

Figure 5 – A research vessel with submerged equipment prepared for scientific exploration.
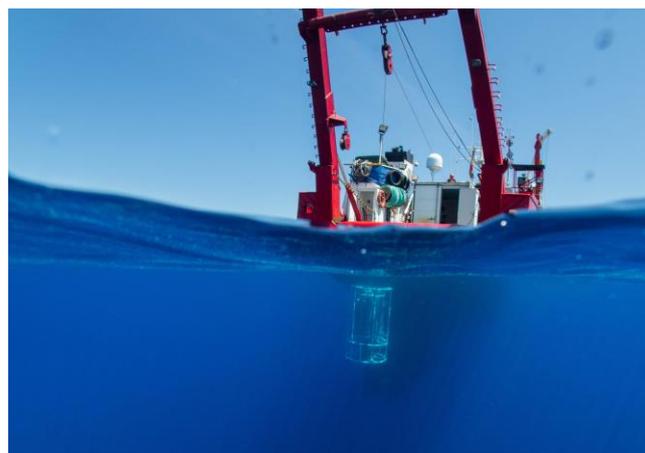
Source: Adobe Stock (stock.adobe.com)

B.2 Data interoperability and integration

Overview and novelty

Participants highlighted a shift towards enabling technologies that support large-scale interoperability and data integration across multiple ocean observation systems.

As noted in the topic on sensor-level data fusion (Earth observation and *in-situ*, A3) , this shift illustrates the broader enablers of data fusion: unified data pipelines that integrate different formats and sensor streams, common metadata standards, harmonised processing workflows, and explainable AI models capable of operating across multiple types of data.

Novelties in these domains include integrated Global Information System (GIS) platforms for reef monitoring; machine learning systems that merge water column measurements done by research vessels with Argo float[10] profiles (vertical

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[9] As noted in topic A.2, cost efficiency—particularly for *in-situ* applications—should be assessed across the full life cycle, including energy efficiency during operation, which in the future can even partially rely on self-powered devices.

[10] Argo floats are autonomous robotic instruments that drift with ocean currents and regularly dive to depths of about 2,000 m to measure temperature and salinity in the upper ocean. Theytransmit their data via satellite as part of the global Argo observing program.

measurements of ocean properties); and tools that bring together genomic, environmental and habitat data to support climate-resilient restoration decisions. They also include real-time digital twins that act as an integration of different data layers.

Together, these solutions connect data that were previously isolated: imagery, biogeochemical observations, genomic baselines, autonomous-vehicle telemetry and fixed-station time series.

Applications and opportunities

Improved interoperability enables, for example, more reliable reef early-warning systems – detecting bleaching events and disease outbreaks sooner - more consistent assessments of long-term oxygen loss, better selection of donor populations for restoration under possible future climate conditions ("climate-smart" planning), and integrated operational intelligence for mapping, modelling and digital-twin applications.

Shared interfaces and standard outputs support cross-disciplinary collaboration. Together, these developments strengthen links between observing networks, management agencies and modelling communities, while facilitating alignment with services such as Copernicus and the European Marine Observation and Data Network (EMODnet).

Challenges and future development

Achieving seamless integration requires advances in metadata harmonisation, common quality control procedures, improvement of data accuracy, multi-modal data alignment and governance of shared data pipelines.

Technical barriers include uncertainty handling, correcting sensor biases, improving annotations of imagery and genomic datasets, and managing the significant computational demand of a continuous data integration.

Longer-term needs include higher-resolution coastal-level solutions, modelling approaches that integrate physical ocean processes with data-driven and AI-based methods, and clear guidance on sharing sensitive data. Robust frameworks will be also needed to ensure transparency and to allow solutions to scale-up to other regional and national systems.

Sources: [65, 66, 67, 68, 69, 70, 71]

Figure 6 – The Ulyx, and autonomous underwater vehicle (AUV) developed by Ifremer
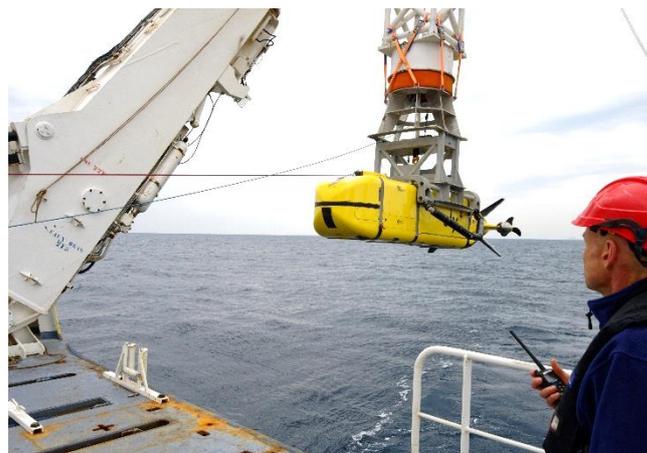
Source: Ifremer, Olivier Dugornay (image.ifremer.fr)

B.3 Autonomous surface and underwater vehicles

Overview and novelty

This was one of the most frequently mentioned topics in the pre-workshop scan, and participants emphasised that although autonomous vehicles have existed for years, there are interesting recent developments in this domain.

The signals collectively show a shift from single, remotely operated platforms to intelligent fleets of autonomous surface vessels (ASVs) and autonomous underwater vehicles (AUVs) operating as coordinated swarms with multiple sensors and onboard processing.

This trend is reinforced by recent advances in edge computing[11], improved perception (sonar, cameras, point clouds), secure communications, and increasingly autonomous decision-making. Together, these developments are transforming what ocean observation platforms can do at sea, and how long missions can last.

Long-range, wave- or solar-powered "resident" uncrewed surface vessels (USVs) could significantly extend mission duration. Their distributed sensing capabilities and swarm-based operation enable much wider area coverage, reducing the need for extensive ship time and the associated costs of operating crewed research vessels over long periods.

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[11] When needed, additional processing can be offloaded to shore-based or cloud systems to handle more computationally intensive tasks.

Applications and opportunities

For ocean observation, these innovations enable persistent and wide-area monitoring, from deep-ocean mapping with coordinated ASV clusters to high-resolution water-quality and habitat surveys.

Hybrid swarms of ASVs and AUVs can follow pollution plumes, support adaptive sampling through the water column, or provide rapid assessments after storms or floods.

Beyond environmental science, the same enabling technology can support offshore infrastructure inspection, maritime safety and search-and-rescue.

Their dual-use nature is particularly clear: secure autonomy, long endurance and coordinated sensing are valuable for both civilian uses (e.g. environmental management) and for defence (e.g. situational awareness).

Challenges and future development

Major challenges include reliable communication and navigation (cooperative included) in acoustically difficult and GNSS[12]-denied environments, as well as managing tight energy and processing budgets on small vehicles.

Innovation in on-board energy storage and low-maintenance energy generation—such as improved batteries, hybrid power systems, wave-energy harvesting or more efficient solar integration—will be essential to achieve longer deployments and support more capable onboard computing.

Ensuring secure, interference-resistant links is also vital for coordinated swarm behaviour[13] and human oversight. Scaling heterogeneous fleets will require shared standards for interoperability, communication formats and data quality.

Finally, updated regulatory frameworks, together with sustained investment in testing infrastructure, will determine how quickly these systems can move into more routine ocean-observation missions.

Sources: [72, 73, 74, 75, 76, 77, 78, 79, 80, 81]

Box 4: Artificial Intelligence

AI emerged as a key enabling technology across many of the priorities identified by participants. Several AI-related capabilities have already been discussed in previous topics. The points below provide an additional overview, bringing together the broader set of ways in which AI enhances data collection and underpins enabling and advanced capabilities.

- **Data fusion and reconstruction**: AI models integrate data from multiple sources and reconstruct incomplete or missing ocean observations, providing a more comprehensive and continuous view of ocean dynamics.
- **Signal processing and noise reduction**: AI algorithms separate target signals (e.g., marine mammal calls) from complex acoustic backgrounds and filter environmental interference from sensor data.
- **Predictive modelling and forecasting**: Deep learning and hybrid AI-physical models are used for forecasting ocean phenomena (e.g., El Niño, storm surges, sea surface temperature), supporting early warning systems and resource management.
- **Automated feature extraction and knowledge discovery**: AI classification enhances the identification of complex oceanographic features (e.g., eddies/whirlpools, internal waves, oil spills, marine organisms) and the extraction of actionable insights from massive datasets, surpassing traditional methods in speed and precision. It enables better genomic data processing as AI can help match environmental DNA sequences to reference databases.
- **Ecosystem and pollution management**: AI-driven systems already support real-time monitoring, waste tracking, and management of marine pollution, as well as health surveillance of ocean organisms, enabling more effective conservation and policy interventions.
- **Decision support and adaptive management**: AI-powered platforms automate data processing, reduce bottlenecks, and provide decision support tools for adaptive

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[12] Global Navigation Satellite Systems (GNSS), for example systems such as the EU's Galileo and the United States' Global Positioning System (GPS)

[13] Swarm behaviour in autonomous vehicles refers to the coordinated actions of multiple autonomous systems—such as drones, underwater robots, or ground vehicles—that operate together as a collective, much like a swarm of insects, birds, or fish.

management of marine resources and conservation efforts.

- **Autonomous platform and vehicle control**: AI enables real-time perception, obstacle avoidance, adaptive sampling decisions, and coordinated behaviour in autonomous fleets (see topic B.3).

Despite rapid progress, some challenges remain, such as data inconsistency, limited labelled datasets, and the need for standardised frameworks. Integrating physical oceanographic knowledge with AI, developing physics-informed models, and fostering international collaboration are critical for advancing the field.

Sources : [82, 83, 84, 85, 86, 87, 88, 89]

Contextual factors

The following topics highlight contextual factors shaping the development and uptake of ocean observation technologies and innovations. They stem from an aggregation of participants' insights[14], re-organised using the STEEP[15] framework.

Social

Growing expectations for transparent, verifiable and high-quality environmental data shape the demand for ocean observation.

Public trust is influenced by the visibility of phenomenon at different scales, from climate change impacts to harmful algal blooms, and pressures on coastal communities. These create stronger calls for early detection, adaptation and remediation actions.

At the same time, social acceptance of new observation methods depends on transparency and clear communication, especially when the data will support politically sensitive decisions such as marine protected area (MPA) or blue-carbon credits[16].

Scientific communities themselves face social pressures due to the loss of domain experts, especially taxonomists, and gaps in biodiversity reference knowledge. These weaken the capacity to interpret new biological data streams. [17]

Fragmentation and siloed working habits across different players and fields limits collaboration. Stronger networking between researchers, engineers and industry should be fostered to counteract this.

Philanthropic interest in biodiversity and climate can expand the space for societal engagement and co-funding of observation efforts.

Finally, global inequalities act as a constraint. The lack of observations in the Global South, for example, creates uneven knowledge and limits the capacity to assess global climate impacts.

Greater involvement of local communities, researchers and regional institutions—paired with open access to data and standards—will be needed to avoid widening these data gaps and to support fair and inclusive ocean governance.

Technological

The effectiveness of new observation technologies depends heavily on underlying scientific and organisational conditions. A deeper understanding of ecosystem functioning—including microbial communities within ecosystems, the size distribution of organisms across trophic levels and complex biological interactions—and more complete biological reference databases are essential to interpret data meaningfully. Without these scientific foundations, even advanced sensing platforms cannot deliver credible outputs.

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[14] These factors were analysed initially using an adapted version of the "Triangle of the Future" framework [92], a foresight method that maps three competing forces: the pull of the future, the push of the present, and the weight of history. It can be used as a stand-alone method or in conjunction with others. For this project, the authors explored 3 types of contextual factors connected with those three temporal dimensions: drivers which are high-level factors that trigger or shape significant contextual changes and pull technological development and uptake into the future; enablers, or opportunities, that are present-day conditions that create a fertile ground for innovation to occur and therefore push technologies forward; and barriers, or challenges, that can be seen as past and present constraints ("weight") that hinder technological development and uptake.

[15] STEEP - Social, Technological, Economic, Environmental and Political/Policy factors.

[16] Carbon markets have emerged as a practical tool for providing the necessary funding for conserving and restoring nature, including in water-based ecosystems. They quantify and verify the carbon sequestration resulting from conservation and restoration actions and translate them into tradable carbon credits. [93]

[17] There is an established concept in biodiversity science called the "taxonomic impediment" — a shortage of trained taxonomists and incomplete biodiversity reference knowledge that limits scientific capacity to identify and interpret biological data. [94]

As previously stated, data interoperability remains a central condition. Standards for data resolution, metadata, reporting formats, and minimum quality-control practices are required to ensure comparability across countries and observation systems.

Connecting national and project-level data streams to major aggregators—such as the European Marine Observation and Data Network (EMODnet), European Global Ocean Observing System (GOOS) and the European Open Science Cloud (EOSC)—could create the backbone for European-level services.

Bridging new methods (e.g. eDNA) with traditional observations requires agreed protocols, intercomparison, and shared reference materials.

Infrastructure and collaboration also play enabling roles. Offshore industries (wind, aquaculture, cables) and vessels of opportunity provide new platforms for sensors, lowering deployment barriers.

However, uptake of new methods such as eDNA is hindered by a lack of standardised reference materials, unresolved methodological uncertainties, and challenges in integrating these approaches into existing frameworks, including the EU Marine Strategy Framework Directive (MSFD).

Economic

Economic pressures strongly influence the feasibility of sustained ocean observation. Many countries face significant budget constraints and competing priorities, which reduce long-term commitments to infrastructure, maintenance and data management.

Achieving cost-effectiveness of sensors requires considering the full lifecycle: not only manufacturing costs but also durability, energy efficiency, maintenance requirements, and ease of use. Sensors requiring constant expert oversight or frequent servicing ultimately prove more expensive than robust systems with higher upfront costs.

Discontinuous observation funding, short project durations, and calls imposing excessive administrative burden (relative to available budgets), reduce the scientific and operational impact. The high cost of development, testing and demonstration—often exceeding the scope of a single project—makes it difficult to reach high Technology Readiness Level (TRL) or fully deploy innovations.

Figure 7 – A fish farm in Greece

Source: Adobe Stock (stock.adobe.com)

At the same time, the financial sector is creating new incentives. Blue bonds and blue carbon credits require verifiable and traceable data to ensure integrity. This increases demand for standardised, high-quality observations and rigorous quality control. It also creates opportunities for science-industry partnerships to produce the datasets required for these finance instruments.

Industry presence in offshore activities can reduce costs and expand observational capacity. For example, using offshore wind farms, aquaculture sites, subsea cables (see previous section) or other infrastructure as observation platforms increases the chances of return on investment and leverages existing assets.

Cooperation with maritime industries through vessels of opportunity (see previous section) also lowers deployment costs and can engage local communities (as mentioned under social factors).

Nonetheless, sustained funding for existing observation platforms remains essential to maintain data flow and avoid system degradation.

Environmental

Rapid environmental change is one of the strongest forces shaping the future of ocean observation, an activity that by default is already developed in an often-hostile environment to humans and equipment.

Climate change, extreme events, ocean acidification, sea-ice loss and altered ecosystem services heighten demand for continuous, high-resolution data. Also,

harmful algal bloom expansion, coastal hypoxia[18] and shifting biodiversity patterns require early event detection and more refined monitoring of ecosystem function. Polar regions and other under-observed areas are becoming strategic environmental priorities.

Biodiversity considerations amplify these pressures. The need to quantify biodiversity, track ecosystem size structure, and assess restoration outcomes (including blue carbon ecosystems) pushes observational requirements beyond physical variables.

The UN's BBNJ agreement (see "scope and policy context" subsection) introduces expectations for an effective monitoring of protected marine areas in zones beyond national jurisdiction, further expanding demand for globally coherent data.

Environmental impacts from human activities—including shipping, fishing, offshore energy production and aquaculture—justify the need for improved monitoring to support robust, data-rich environmental impact assessments.

At the same time, expanding coastal development and offshore infrastructure increase ecological risks, reinforcing the need for adaptive management informed by continuous and reliable environmental observations.

Figure 8 – The hybrid ROV Ariane developed by Ifremer
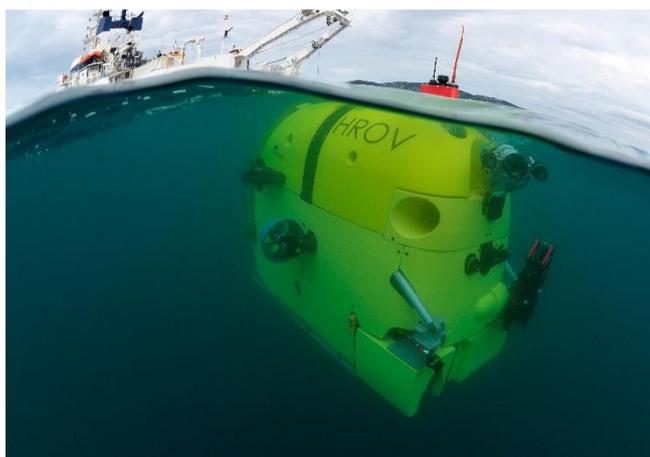
Source: Ifremer, Olivier Dugornay (image.ifremer.fr)

Political

The current geopolitical context introduces significant uncertainty. Worldwide political changes,

conflicts, and fluctuating interest in climate and science affect international cooperation and long-term planning.

These dynamics influence access to waters used by multiple countries, data exchange, and the stability of cross-border observational efforts. Geopolitical tensions can also elevate the dual-use dimension of ocean data, bringing additional challenges to international governance and partnerships. Limitations to data capture and access and even to develop scientific activity, can further bias data and even hinder progress in Artificial Intelligence (see Box 4 for more details).

European-level initiatives such as the development on legislative framework on sensors, can play a decisive role. Continuous coordination avoids grey areas in regulation as well as fragmentation between national and EU monitoring obligations (e.g. homogenisation of the EEZ-exclusive economic zone access for oceanographic vessels).

Political commitment to treating ocean observation as a critical infrastructure varies across countries, affecting potentially funding continuity and institutional support.

Security considerations increasingly shape political priorities. Concerns around the safety and cybersecurity of ships and offshore infrastructure—cables, wind farms, subsea assets—drive demand for monitoring capabilities with security relevance.

Defence-related interest in ocean observation technologies can accelerate investment, but may also introduce restrictions on access, data sharing or platform use. Political choices will determine whether this dual-use dynamic becomes a barrier or an opportunity for Europe.

Conclusions

Considering the discussions and results of this exercise, technology convergence is emerging as the defining principle shaping next-generation ocean observation.

The complexity of environmental change, the rising demands of governance frameworks, and the need for trusted data make it clear that no single

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[18] Low oxygen levels in the water—specifically, oxygen concentrations too low to support most marine life. Hypoxia disrupts ecosystems, harms fisheries, and signals declining coastal water quality.

technology can meet present or future requirements.

Progress will depend on integrated systems that combine multiple sensing approaches, autonomous platforms and AI-enabled analytics.

Participants emphasised that investing in enabling technologies is essential for Europe to expand and improve its observing capacity. Meeting tomorrow's challenges—climate impacts, biodiversity loss, risks to the blue economy and new geopolitical pressures—will require more continuous measurements, larger data volumes, and their faster analysis.

This will depend not only on improved sensors and platforms, but also on the systems behind them: data fusion, high-quality metadata, robust interoperability, shared reference databases and adherence to common standards. Creating more cost-efficient sensors and systems will also be key for scaling up this activity.

Autonomy was highlighted as a major opportunity. Advances in energy systems, long-endurance vehicles and onboard autonomous decision-making can make observation more cost-effective and persistent across the ocean, from the surface to deep waters.

New sensing technologies—genomic, acoustic and optical—combined with AI and robotics offer enhanced biodiversity monitoring, from microbes to fish and marine mammals.

Industry was also recognised as a strong driver of research and development, particularly where commercial and environmental interests converge.

Participants stressed that *in-situ* monitoring remains irreplaceable. While satellite and AI-driven analytics can enrich understanding, they cannot substitute the physical samples, direct measurements and long-time series required to build scientific knowledge. In fact, *in-situ* observations provide the reference data used to train, calibrate, and validate most AI applications in ocean observation.

A diverse set of platforms—ranging from ROVs and AUVs to Argo floats, vessels, buoys and animal-borne sensors—will therefore remain essential.

Finally, as ocean observation becomes more strategically important, investment should be assessed in terms of long-term value, cost-effectiveness, modularity and system-level

integration.

The future of ocean observation therefore depends on convergence: integrating technologies, aligning scientific methods, harmonising governance frameworks, maintaining sustained investment, and fostering collaborative networks across disciplines and borders.

Figure 9 – A 'swirling tornado' of Barracudas

Source: Adobe Stock (stock.adobe.com)

References

[1] E. Amanatidou, M. Butter, V. Carabias, T. Könnölä, M. Leis, O. Saritas, P. Schaper-Rinkel and V. van Rij, "On concepts and methods in horizon scanning: Lessons from initiating policy dialogues on emerging issues," *Science and Public Policy,* vol. 39, no. 2, pp. 208-221, 2012.

[2] J. Farinha, L. Vesnic Alujevic and A. Polvora, "Scanning deep tech horizons: participatory collection and assessment of signals and trends," Publications Office of the European Union, Luxembourg, 2023.

[3] P. Dannemand Andersen, M. Bevolo, I. Ilevbare, E. Malliaraki, R. Popper and M. Spaniol, Technology Foresight for Public Funding of Innovation: Methods and Best Practices, L. Vesnic Alujevic, J. Farinha and A. Polvora, Eds., Luxembourg: Publications Office of the European Union, 2023.

[4] European Commission, "Ocean Observation," European Commission, 2025. [Online]. Available: https://maritime-forum.ec.europa.eu/theme/marine-knowledge/ocean-observation_en.

[5] European Commission, "The European Ocean Pact," European Commission, 2025. [Online]. Available: https://oceans-and-fisheries.ec.europa.eu/european-ocean-pact_en.

[6] Mercator Ocean International, "EU4OceanObs," Mercator Ocean International, 2025. [Online]. Available: https://www.eu4oceanobs.eu/.

[7] Mercator Ocean International, "Copernicus Marine Service," Mercator Ocean International, 2025. [Online]. Available: https://marine.copernicus.eu/.

[8] European Commission, "European Marine Observation and Data Network (EMODnet)," European Commission, 2025. [Online]. Available: https://emodnet.ec.europa.eu/en.

[9] JPI Oceans, "JPI Oceans," JPI Oceans, 2025. [Online]. Available: https://jpi-oceans.eu/en.

[10] European Commission, "EU Mission: Restore our Ocean and Waters," European Commission, 2025. [Online]. Available: https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/restore-our-ocean-and-waters_en.

[11] United Nations, "Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction - BBNJ Agreement," United Nations, 2025. [Online]. Available: https://www.un.org/bbnjagreement/en.

[12] Oceanological Observatory of Banyuls-sur-Mer, "BOSS ePlatform," Oceanological Observatory of Banyuls-sur-Mer, [Online]. Available: https://www.obs-banyuls.fr/en/research/projects-of-the-research-federation/boss-eplatform.html.

[13] A. Hendricks, C. Mackie, E. Luy, C. Sonnichsen, J. Smith, I. Grundke, M. Tavasoli, A. Furlong, R. G. Beiko, J. LaRoche and V. Sieben, "Compact and automated eDNA sampler for in situ monitoring of marine environments," *Scientific Reports,* 2023.

[14] C. Preston, K. Yamahara, D. Pargett, C. Weinstock, J. Birch, B. Roman, S. Jensen, B. Connon, R. Jenkins, J. Ryan and C. Scholin, "Autonomous eDNA collection using an uncrewed surface vessel over a 4200-km transect of the eastern Pacific Ocean," *Environmental DNA,* vol. 6, no. 1, 2023.

[15] A. Borja, T. Berg, H. Gundersen, A. G. Hagen, K. Hancke, S. Korpinen, M. Leal, T. Luisetti, I. Menchaca, C. Murray, G. Piet, S. Pitois, N. Rodríguez-Ezpeleta, J. Sample, E. Talbot and M. Uy, "Innovative and practical tools for monitoring and assessing biodiversity status and impacts of multiple human pressures in marine systems," *Environmental Monitoring and Assessment,* vol. 196, 2024.

[16] INESC Brussels HUB, "Scientists collect eDNA samples in the extreme environment of the Arctic melting glaciers autonomously," Phys.org, 2024. [Online]. Available: https://phys.org/news/2024-01-scientists-edna-samples-extreme-environment.html.

[17] Oceanographic Magazine, "New eDNA sampler to transform biodiversity studies, scientists say," Oceanographic Magazine, 2024. [Online]. Available: https://oceanographicmagazine.com/news/new-edna-sampler-to-transform-biodiversity-studies-scientists-say/.

[18] NatureMetrics, "NatureMetrics and Dartmouth Ocean Technologies Launch Revolutionary Autonomous Aquatic eDNA Sampling Solution," NatureMetrics, 2024. [Online]. Available: https://www.naturemetrics.com/news/autonomous-aquatic-edna-sampling-solution.

[19] European Commission, "Improving the cost-efficiency of fisheries research surveys and fish stocks assessment using next-generation genetic sequencing methods," 2023. [Online]. Available: https://cinea.ec.europa.eu/publications/digital-publications/improving-cost-efficiency-fisheries-research-surveys-and-fish-stocks-assessment-using-next_en.

[20] Y. C. A. Ip, J. J. M. Chang and D. Huang, "Advancing and Integrating 'Biomonitoring 2.0' with New Molecular Tools for Marine Biodiversity and Ecosystem Assessments," in *Oceanography and Marine Biology*, Boca Raton, 2023.

[21] M. Scriver, A. Zaiko, X. Pochon and U. v. Ammon, "Harnessing decay rates for coastal marine biosecurity applications: A review of environmental DNA and RNA fate," *Environmental DNA,* vol. 5, p. 960–972, 2023.

[22] X. Pochon, H. A. Bowers, A. Zaiko and S. A. Wood, "Advancing the environmental DNA and RNA toolkit for aquatic ecosystem monitoring and management," *PeerJ,* vol. 13, 2025.

[23] W. Li, H. Jia and H. Zhang, "Evaluating the effectiveness of the eRNA technique in monitoring fish biodiversity – A case study in the Qingdao offshore, China," *Global Ecology and Conservation,* vol. 51, 2024.

[24] M. Scriver, U. v. Ammon, X. Pochon, V. Arranz, J.-A. L. Stanton, N. J. Gemmell and A. Zaiko, "Environmental DNA–RNA dynamics provide insights for effective monitoring of marine invasive species," *Environmental DNA,* vol. 6, no. 2, 2024.

[25] M. Mowlem, A. Beaton, R. Pascal, A. Schaap, S. Loucaides, S. Monk, A. Morris, C. L. Cardwell, S. E. Fowell, M. D. Patey and P. López-García, "Industry Partnership: Lab on Chip Chemical Sensor Technology for Ocean Observing," *Frontiers in Marine Science,* vol. 8, 2021.

[26] A. D. Beaton, A. M. Schaap, R. Pascal, R. Hanz, U. Martincic, C. L. Cardwell, A. Morris, G. Clinton-Bailey, K. Saw, S. E. Hartman and M. C. Mowlem, "Lab-on-Chip for In Situ Analysis of Nutrients in the Deep Sea," *ACS Sensors,* vol. 7, no. 1, 2022.

[27] T. Yin, S. Papadimitriou, V. M. Rérolle, M. Arundell, C. L. Cardwell, J. Walk, M. R. Palmer, S. E. Fowell, A. Schaap, M. C. Mowlem and S. Loucaides, "A Novel Lab-on-Chip Spectrophotometric pH Sensor for Autonomous In Situ Seawater Measurements to 6000 m Depth on Stationary and Moving Observing Platforms," *Environmental Science & Technology,* vol. 55, no. 21, 2021.

[28] A. Schaap, S. Papadimitriou, E. Mawji, J. Walk, E. Hammermeister, M. Mowlem and S. Loucaides, "Autonomous Sensor for In Situ Measurements of Total Alkalinity in the Ocean," *ACS Sensors,* vol. 10, no. 2, 2025.

[29] MIT Sea Grant, "SEAPERCH II," MIT Sea Grant, 2025. [Online]. Available: https://seagrant.mit.edu/seaperch2/.

[30] A. Wilson, "SeaPerch: A robot with a mission," MIT News, 2025. [Online]. Available: https://news.mit.edu/2025/seaperch-robot-with-a-mission-0320.

[31] SCOOP, "SCOOP - Solutions for Cost-Effective Ocean Observation Platform," SCOOP-Ocean website, 2025. [Online]. Available: https://www.scoop-ocean.org/.

[32] IFREMER, "CHEMINI - CHEmical MINIaturised analyser," IFREMER, 2025. [Online]. Available: https://rd-technologiques.ifremer.fr/Moyens/Laboratoire-de-chimie-analytique/CHEMINI2.

[33] M. Archer, J. Wang, P. Klein, G. Dibarboure and L.-L. Fu, "Wide-swath satellite altimetry unveils global submesoscale ocean dynamics," *Nature,* vol. 640, p. 691–696, 2025.

[34] G. Hawkins, "Small Currents, Big Impact: Satellite Breakthrough Reveals Hidden Ocean Forces," Texas A&M University, 2025. [Online]. Available: https://stories.tamu.edu/news/2025/05/27/small-currents-big-impact-satellite-breakthrough-reveals-hidden-ocean-forces/.

[35] P. Miron, F. J. Beron-Vera, L. Helfmann and P. Koltai, "Transition paths of marine debris and the stability of the garbage patches," *Chaos,* vol. 31, no. 3, 2021.

[36] E. M. Duncan, A. Davies, A. Brooks, G. W. Chowdhury, B. J. Godley, J. Jambeck, T. Maddalene, I. Napper, S. E. Nelms, C. Rackstraw and H. Koldewey, "Message in a bottle: Open source technology to track the movement of plastic pollution," *PLOS ONE,* vol. 17, no. 5, 2022.

[37] K. Topouzelis, D. Papageorgiou, G. Suaria and S. Aliani, "Floating marine litter detection algorithms and techniques

using optical remote sensing data: A review," *Marine Pollution Bulletin,* vol. 170, 2021.

[38] À. S. Gómez, L. Scandolo and E. Eisemann, "A learning approach for river debris detection," *International Journal of Applied Earth Observation and Geoinformation,* vol. 107, 2022.

[39] A. Xenaki, P. Gerstoft, E. Williams and S. Abadi, "Overview of distributed acoustic sensing: Theory and ocean applications," *The Journal of the Acoustical Society of America,* vol. 158, no. 1, 2025.

[40] D. Gräff, B. P. Lipovsky, A. Vieli, A. Dachauer, R. Jackson, D. Farinotti, J. Schmale, J.-P. Ampuero, E. Berg, A. Dannowski, A. Kneib-Walter, M. Köpfli, H. Kopp, E. v. d. Loo and D. M. Flores, "Calving-driven fjord dynamics resolved by seafloor fibre sensing," *Nature,* vol. 644, pp. 404-412, 2025.

[41] J. Lin, S. Fang, R. He, Q. Tang, F. Qu, B. Wang and W. Xu, "Monitoring ocean currents during the passage of Typhoon Muifa using optical-fiber distributed acoustic sensing," *Nature Communications,* vol. 15, 2024.

[42] PLOCAN, "The ATLAS Project Turns Submarine Cables into "Ears" to Protect the Atlantic," PLOCAN, 2025. [Online]. Available: https://plocan.eu/en/the-atlas-project-turns-submarine-cables-into-ears-to-protect-the-atlantic.

[43] S. Stefanni, L. Mirimin, D. Stanković, D. Chatzievangelou, L. Bongiorni, S. Marini, M. V. Modica, E. Manea, F. Bonofiglio, J. d. R. Fernandez, N. Cukrov, A. Gavrilović, F. C. D. Leo and J. Aguzzi, "Framing Cutting-Edge Integrative Deep-Sea Biodiversity Monitoring via Environmental DNA and Optoacoustic Augmented Infrastructures," *Frontiers in Marine Science,* vol. 8, 2022.

[44] I. Lior, A. Sladen, D. Rivet, J.-P. Ampuero, Y. Hello, C. Becerril, H. F. Martins, P. Lamare, C. Jestin, S. Tsagkli and C. Markou, "On the Detection Capabilities of Underwater Distributed Acoustic Sensing," *Journal of Geophysical Research: Solid Earth,,* vol. 126, 2021.

[45] A. F. Baird, J. P. Morten, V. Oye and S. Bjørnstad, "Ocean Space Surveillance and Real-Time Event Characterization Using Distributed Acoustic Sensing on Submarine Networks," *Seismological Research Letters,* vol. 96, no. 2A, 2025.

[46] J. R. Potter, E. Wengle, R. A. Rørstadbotnen, H. Dong and T. A. Reinen, "Distributed Acoustic Sensing of Underwater Acoustic Communication Packets: Effects of Frequency and Incidence Angle," in *WUWNET '24: 18th International Conference on Underwater Networks & Systems*, Šibenik, Croatia, 2024.

[47] E. F. Williams, M. R. Fernández-Ruiz, R. Magalhaes, R. Vanthillo, Z. Zhan, M. González-Herráez and H. F. Martins, "Distributed sensing of microseisms and teleseisms with submarine dark fibers," *Nature Communications,* vol. 10, 2019.

[48] L. Thiem, S. Wienecke, K. Taweesintananon, M. Vaupel and M. Landrø, "Ship noise characterization for marine traffic monitoring using distributed acoustic sensing," in *IEEE International Workshop on Metrology for the Sea; Learning to Measure Sea Health Parameters (MetroSea)*, La Valletta, Malta, 2023.

[49] K. Borgmann, "New study advances acoustic monitoring of endangered whale," Cornell University, 2025. [Online]. Available: https://news.cornell.edu/stories/2025/02/new-study-advances-acoustic-monitoring-endangered-whale.

[50] The Journal of the Acoustical Society of America, "'Fishial' Recognition: Neural Network Identifies Coral Reef Sounds," AIP Publishing – news, 2025. [Online]. Available: https://publishing.aip.org/publications/latest-content/fishial-recognition-neural-network-identifies-coral-reef-sounds/.

[51] S. McCammon, N. Formel, S. Jarriel and T. A. Mooney, "Rapid detection of fish calls within diverse coral reef soundscapes using a convolutional neural network," *The Journal of thhe Acousical Society of America,* vol. 157, no. 3, 2025.

[52] A. Raza, S. Zongxin, G. Qiao, M. Javed, M. Bilal, H. H. Zuberi and M. Mohsin, "Automated classification of humpback whale calls in four regions using convolutional neural networks and multi scale deep feature aggregation (MSDFA)," *Measurement,* vol. 255, 2025.

[53] Y. Zhao, S. S. Afzal, W. Akbar, O. Rodriguez, F. Mo, D. Boyle, F. Adib and H. Haddadi, "Towards battery-free machine learning and inference in underwater environments," in *HotMobile '22: 23rd Annual International Workshop on Mobile Computing Systems and Applications*, Tempe, Arizona, USA, 2022.

[54] E. Schall, I. I. Kaya, E. Debusschere, P. Devos and C. Parcerisas, "Deep learning in marine bioacoustics: a benchmark for baleen whale detection," *Remote Sensing in Ecology and Conservation,* vol. 10, no. 5, 2024.

[55] J.-F. Laplante, M. A. Akhloufi and C. Gervaise, "Deep Learning for Marine Bioacoustics and Fish Classification Using Underwater Sounds," in *Canadian Conference on Electrical and Computer Engineering (CCECE)*, Halifax, NS, Canada, 2022.

[56] E. L. White, H. Klinck, J. M. Bull, P. R. White and D. Risch, "One size fits all? Adaptation of trained CNNs to new marine acoustic environments," *Ecological Informatics,* vol. 78, 2023.

[57] Z. Göröcs, M. Tamamitsu, V. Bianco, P. Wolf, S. Roy, K. Shindo, K. Yanny, Y. Wu, H. C. Koydemir, Y. Rivenson and A. Ozcan, "A deep learning-enabled portable imaging flow cytometer for cost-effective, high-throughput, and label-free analysis of natural water samples," *Light: Science & Applications,* vol. 7, 2018.

[58] S. Luo, K. T. Nguyen, B. T. T. Nguyen, S. Feng, Y. Shi, A. Elsayed, Y. Zhang, X. Zhou, B. Wen, G. Chierchia, H. Talbot, T. Bourouina, X. Jiang and A. Q. Liu, "Deep learning-enabled imaging flow cytometry for high-speed Cryptosporidium and Giardia detection," *Cytometry Part A,* vol. 99, no. 11, 2021.

[59] G. Ciaparrone, D. Pirone, P. Fiore, L. Xin, W. Xiao, X. Li, F. Bardozzo, V. Bianco, L. Miccio, F. Pan, P. Memmolo, R. Tagliaferri and P. Ferraro, "Label-free cell classification in holographic flow cytometry through an unbiased learning strategy," *Lab on a Chip,* vol. 24, 2024.

[60] J. Fontes, B. Macena, S. Solleliet-Ferreira and e. al., "The advantages and challenges of non-invasive towed PILOT tags for free-ranging deep-diving megafauna," *Animal Biotelemetry,* vol. 10, no. 39, 2022.

[61] K. Kraft, L. Haraguchi, H. Hällfors, S. Suikkanen, P. Ylöstalo, S. Kielosto, A. Skyttä, L. Laakso, M. Honkanen, M. Kahru and J. Seppälä, "Monitoring cyanobacteria blooms with complementary measurements – a similar story told using high-throughput imaging, optical sensors, light microscopy, and satellite-based methods," *Harmful Algae,* vol. 147, 2025.

[62] Fishing Vessel Ocean Observing Network (FVON), "Fishing Vessel Ocean Observing Network," Fishing Vessel Ocean Observing Network, 2025. [Online]. Available: https://www.fvon.org/.

[63] C. V. Vranken, J. Jakoboski, J. W. Carroll, C. Cusack, P. Gorringe, N. Hirose, J. Manning, M. Martinelli, P. Penna, M. Pickering, A. M. Piecho-Santos, M. Roughan, J. d. Souza and H. Moustahfid, "Towards a global Fishing Vessel Ocean Observing Network (FVON): state of the art and future directions," *Frontiers in Marine Science,* vol. 10, 2023.

[64] T. L. Rosa, A. M. Piecho-Santos, R. Vettor and C. G. Soares, "Review and Prospects for Autonomous Observing Systems in Vessels of Opportunity," *Journal of Marine Science and Engineering,* vol. 9, no. 4, 2021.

[65] A. Chowdhury, "Can artificial intelligence save the Great Barrier Reef?," University of South Australia, 2025. [Online]. Available: https://unisa.edu.au/media-centre/Releases/2025/can-artificial-intelligence-save-the-great-barrier-reef/.

[66] T. Ito, A. Cervania, K. Cross, S. Ainchwar and S. Delawalla, "Mapping Dissolved Oxygen Concentrations by Combining Shipboard and Argo Observations Using Machine Learning Algorithms," *Journal of Geophysical Research: Machine Learning and Computation,* vol. 1, no. 3, 2024.

[67] C. Barzler, "Novel Machine Learning Techniques Measure Ocean Oxygen Loss More Accurately," Georgia Institute of Technolog, 2024. [Online]. Available: https://research.gatech.edu/novel-machine-learning-techniques-measure-ocean-oxygen-loss-more-accurately.

[68] G. V. Wood, K. J. Griffin, M. v. d. Mheen, M. F. Breed, J. M. Edgeloe, C. Grimaldi, A. J. P. Minne, I. Popovic, K. Filbee-Dexter, M. J. H. v. Oppen, T. Wernberg and M. A. Coleman, "Reef Adapt: A tool to inform climate-smart marine restoration and management decisions," *Communications Biology,* vol. 7, 2024.

[69] Flinders University, "Marine genetics to help restore coastlines," Flinders University, 2024. [Online]. Available: https://news.flinders.edu.au/blog/2024/10/31/marine-genetics-to-help-restore-coastlines/.

[70] R. Tardiff, "11 innovations deepening our understanding of the ocean through data," World Economic Forum, 2023. [Online]. Available: https://www.weforum.org/stories/2023/01/davos23-11-innovations-deepening-our-understanding-of-the-ocean-through-data/.

[71] Mercator Ocean International, "Digital Twin of the Ocean," Mercator Ocean International, 2022. [Online]. Available: https://digitaltwinocean.mercator-ocean.eu/.

[72] Z. Kassuba, M. Goldenbogen, C. Jannetta, X. Vicent and E. I. Sarda, "Mercator Ocean International," in *OCEANS 2024,* Halifax, 2024.

[73] D. Ma, X. Chen, W. Ma, H. Zheng and F. Qu, "Neural Network Model-Based Reinforcement Learning Control for AUV 3-D Path Following," *IEEE Transactions on Intelligent Vehicles,* vol. 9, no. 1, pp. 893-904, 2024.

[74] F. Liu, H. Chen and L. Xie, "A Novel Multi-AUV Cooperative Navigation Method Using Information Incorporation," in *OCEANS 2022,* Hampton Roads, 2022.

[75] W. Zhan, Y. Tian, Q. Sang, F. Zheng, Q. Jin and J. Yu, "Optimization of Sensing Locations of Autonomous Underwater Vehicles for Optimal Environmental Prediction and Acoustic Target Tracking," in *OCEANS 2022,* Hampton Roads, 2022.

[76] S. Yin, N. Xu, Z. Shi and Z. Xiang, "Collaborative path planning of multi-unmanned surface vehicles via multi-stage constrained multi-objective optimization," *Advanced Engineering Informatics,* vol. 65, 2025.

[77] A. Tantillo, "Surface-based sonar system could rapidly map the ocean floor at high resolution," MIT News, 2024. [Online]. Available: https://news.mit.edu/2024/surface-based-sonar-system-could-rapidly-map-ocean-floor-high-resolution-1218.

[78] S. Wu, L. Zhang, C. Tang and Y. Gao, "Underwater Unmanned Vehicle Clusters Cooperative Positioning Method," in *IEEE International Conference on Signal Processing, Communications and Computing,* Baruna Bali, Indonesia, 2024.

[79] CHCNAV, "Hydrographic Surveying Solutions for Bathymetry and Marine Projects," CHCNAV, 2025. [Online]. Available: https://geospatial.chcnav.com/solutions/marine-surveying.

[80] H. Zhen and C. Liu, "An overview of Unmanned Surface Vehicles: Methods, practices, and applications," *Control Engineering Practice,* vol. 164, 2025.

[81] D. Ma, Y. Li, T. Ma and A. M. Pascoal, "The state of the art in key technologies for autonomous underwater vehicles: a review," *Engineering,* 2025.

[82] X. Li, H. Wang, X. Yang, Q. Xu, L. Guan, L. Gao, X. Zhang, Y. Ren, Y. Liu and W. Chen, "Advances in artificial intelligence ocean remote sensing," *National Remote Sensing Bulletin,* vol. 29, no. 6, 2024.

[83] T. Song, C. Pang, B. Hou, G. Xu, J. Xue, H. Sun and F. Meng, "A review of artificial intelligence in marine science," *Frontiers in Earth Science,* vol. 11, 2023.

[84] C. Dong, G. Xu, G. Han, B. J. Bethel, W. Xie and S. Zhou, "Recent Developments in Artificial Intelligence in Oceanography," *Ocean-Land-Atmoshere Research,* vol. 2022, 2022.

[85] V. Nieves, A. Ruescas and R. Sauzède, "AI for Marine, Ocean and Climate Change Monitoring," *Remote Sensing,* vol. 16, no. 1, 2024.

[86] X. Li, B. Liu, G. Zheng, Y. Ren, S. Zhang, Y. Liu, L. Gao, Y. Liu, B. Zhang and F. Wang, "Deep-learning-based information mining from ocean remote-sensing imagery," *National Science Review,* vol. 7, no. 10, 2020.

[87] E. M. Ditria, C. A. Buelow, M. Gonzalez-Rivero and R. M. Connolly, "Artificial intelligence and automated monitoring for assisting conservation of marine ecosystems: A perspective," *Frontiers in Marine Science,* vol. 9, 2022.

[88] S. Adiyono, M. Arifin, N. Latifah and E. Darmanto, "Artificial Intelligence in Integrated Marine Observing Systems: A Comprehensive Review," *International Journal of Marine Ingineering Innovation,* vol. 10, no. 1, 2025.

[89] A. Mandal and A. R. Ghosh, "AI-driven surveillance of the health and disease status of ocean organisms: a review," *Aquaculture International ,* vol. 32, 2024.

[90] B. L. van Veen and J. Roland Ortt, "Unifying weak signals definitions to improve construct understanding," *Futures,* vol. 134, p. 102837, 2021.

[91] P. Rossel, "Early detection, warnings, weak signals and seeds of change: A turbulent domain of futures studies," *Futures,* vol. 44, no. 3, pp. 229-239, 2012.

[92] S. Inayatullah, "The Futures Triangle: Origins and Iterations," *World Futures Review,* vol. 15, no. 2-4, pp. 112-121, 2023.

[93] S. Farahmand, N. Hilmi and C. M. Duarte, "The rise and flows of blue carbon credits advance global climate and biodiversity goals," *npj Ocean Sustainability,* vol. 4, no. 39, 2025.

[94] M. S. Engel, L. M. P. Ceríaco, G. M. Daniel, P. M. Dellapé, I. Löbl, M. Marinov, R. E. Reis, M. T. Young, A. Dubois, I. Agarwal, P. L. A., M. Alvarado, N. Alvarez, F. Andreone and K. Araujo-Vieira, "The taxonomic impediment: a shortage of taxonomists, not the lack of technical approaches," *Zoological Journal of the Linnean Society,* vol. 193, no. 2, 2021.

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