7. Marine Pollution: Its Sources, Distribution and Solutions

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7.1. Scope and Context

Marine Pollution is a global societal concern that adversely affects marine ecosystem services and human health. To effectively explore and mitigate marine pollution, a combination of advanced technologies and methodologies is essential. These include remote sensing, in-situ sensors, laboratory analyses, modelling, data integration, artificial intelligence and environmental engineers. Together, these capabilities might provide a comprehensive understanding of the fate and behaviours of current and future effects of marine pollution in the ecosystems, to advance their detection, monitoring and remediation and support innovative management and policy strategy to protect marine environments. To develop an effective requirements framework toward marine pollution, educational and public awareness campaigns as well as sustainable practices engagement with national and global initiatives are crucial. International programs and initiatives focused on marine pollution are often collaborative efforts involving multiple countries, organizations, and stakeholders, aimed at strengthening scientific research and monitoring, improve data sharing and collaboration.

An example of an international initiative is the Back to Blue (an initiative of Economist Impact[i] and The Nippon Foundation[ii]) published ‘A global ocean free from the harmful impacts of pollution: Roadmap for action’[iii], in March at the World Ocean Summit. The roadmap is a strategic framework to build a comprehensive evidence base to tackle ocean pollution collectively. Now, the IOC UNESCO Ocean[iv] and UN Environment Programme[v] Secretariats aim to develop an implementation plan for the roadmap. The Ocean Decade also published the 10 Vision 2030[vi] White Papers, each focusing on a specific Ocean Decade Challenge[vii], represent a collaborative effort to develop the science we need for the ocean we want by 2030.

By 2040, the scientific developments and technological advancements are expected to play a crucial role in enhancing our understanding of marine pollution (UNSDG14), restoring marine ecosystems, and ensuring sustainable use of ocean resources. In this frame, the scope of Marine Pollution Grand Challenge is to support a coordinated, collaborative, and collective efforts to develop an economically and environmentally sustainable approach to research infrastructure for current and future marine pollution research, within the context of the other Grand Challenges and the wider UKRI research environment.

7.2. Anticipated Scientific Developments By 2040

Best practices (BP) followed in all facilities to ensure reproducibility, accuracy, and precision and reduce methodological bias. This will produce high-quality data that could be implemented in models and will also help to understand the problem and better inform policy and decision making. These BPs will be available and will be stored in a public repository, e.g. Ocean Best Practices System (OBPS) which was formally adopted as an IOC Project in June 2019, joint sponsored by the IODE and GOOS Programmes. BPs will be agreed by a community of experts and will be available for continuous community review.

Unified Certified Reference Materials (CRMs) to be used in all UK facilities and coordinate with other international initiatives. Facilities will need to report on values from these materials. Some CRMs are available but for some pollutants or groups of them, laboratories need to prepare their own. UK experts will have to agree on protocols to produce these CRMs and intercalibration exercises will also be required. Experts will engage with metrology institutions and national institutes of standards among others to ensure traceability of the material and to secure its production in the future.

Long-term monitoring strategy established. This will include long-term ocean monitoring sentinel stations as recommended in the Ocean Decade Vision 2030 White Papers. These stations will include historical and new stations. Data collected will help to understand trends, help identify hotspots and pollutants of concerns which will help to develop effective control and mitigation strategies.

Ability to deal with complex, high frequency data that provides clear outcomes to the needs of long-term monitoring and assessment programs. Currently, the majority of the data collected through autonomous or high frequency (big data) means is not fit for purpose in monitoring and assessment programs. Artificial Intelligence (AI) and machine learning (ML) may provide some of the answers, but we need to reconsider current monitoring indicators, and how policy tracks environmental changes. Big data will not always provide the critical nuances needed to guide policy, so this requires both bottom-up and top-down rethinking on monitoring frameworks, national and international environmental indicators, and the use of big data to resolve questions, or (at least) add to our understanding of annual and multi-annual changes. **This will also require a unified datasets portal with all available measurements and harmonization.**

UK archives to store samples for sharing and future studies. This will also require sharing sampling methods and storing requirements etc. We need to collect quality samples for future studies (to answer future questions). Having BPs in place for sample collection and preservation will help to fill all requirements. New emerging pollutants are being introduced and discovered every day, and their effects are, in most cases, still unknown. Therefore, these samples will help to carry future investigations by providing the opportunity to access historical samples that might be required. This will need to be taken into account when defining the BPs.

UK database around labs/institutions/companies to increase visibility and collaboration. Efforts from interest parties will be required to keep this database up to date.

Efficient sample collection strategy. Engaging with other scientific areas to collect samples in a more efficient way: reducing time onboard ships by reducing the amount of people required to take samples and increasing the number of samples collected. Onboard technicians and researchers will follow BP protocols for sampling and preserving the samples. This might require a managed database for scientists to engage with planned activities they can join and to publicise any activity that can include extra sampling.

7.3. Key Science Questions, Knowledge Gaps and Uncertainties

Identify real thresholds of toxicity/ecological impact within a multi-stressor system: Addressing marine pollution requires a holistic approach that considers the interconnectedness of pollutants and their combined effects on marine ecosystems. Understanding the interactions of pollutants with other environmental stressors such as physical changes (habitat destruction, temperature shifts, change in pH), or biological factors (invasive species, diseases) is also crucial. To address the impact of pollutants within an environmental and climatic change context means that thresholds can be reached even if individual pollutants are below their harmful levels.

Identify long-term effects, including resilience and transgenerational effects: Pollutants can persist, leading to bioaccumulation and biomagnification in the marine environment. Pollutants not only affect the exposed individuals but might also have consequences for subsequent generations (i.e. affecting mechanisms such as genetic, epigenetic, and developmental pathways) resulting in long-term (and potentially irreversible) ecological impacts.

Assess hotspots of ecological risk as well as human and societal risk: Identify specific marine areas characterized by high levels of biodiversity, significant ecological functions, and intense human activities that pose risks to marine health. These areas could be particularly sensitive to pollution.

Estimate pollutant pathways and fate to assess states and trends: Understanding how pollutants enter, traverse, and persist in the marine environment. This process includes identifying sources, transport mechanisms, chemical transformations, and ultimate sinks or destinations of pollutants.

Identify a common approach to understand the impact of pollution and how to tackle the problem: It will be crucial to find a common approach (due to the vastity of pollutants) to have an overall understanding of the impact. In this regard, the first step will be to reduce complexity. For example, firstly, focus on the functional typology of pollutants (i.e. bioaccumulation, biomagnification, toxicology), secondly, identify a marker of general pollution as a proxy of occurrence and frequency, and finally, identify the main driving vectors (chemical, biological, physical).

7.4. Observation/Product Requirements

7.4.1. Observation

Scaling up from organism to population and ecosystem: This is fundamental to achieve a comprehensive and holistic understanding of pollution impacts (including, for example, habitat alteration and trophic interaction), leading to more effective environmental management and conservation strategies.

Large-scale and temporal data coverage: Robust datasets are fundamental for addressing the complex and evolving challenges posed by marine pollution. It enables the detection of long-term trends and seasonal variation, to assess the level of Chronic Exposure as well as Acute Events (i.e. oil spills), synergistic impacts and the prediction of future scenarios. Policymakers rely on robust data to create effective regulations to control pollution levels and mitigate risks.

7.4.2. Products

Enhance Data availability and statistical analysis to validate modelling: A lot can be done looking at and combining historical data. This will involve establishing a centralized database or repository and fostering national data-sharing agreements as well as enhancing computational infrastructure to support the processing and analysis of large data sets, and investment in developing advanced sensors for real-time monitoring of a wide range of pollutants.

Standardize measurements/best practices for dataset inter-comparability. This should include the developing of protocols (Cookbook concept, i.e. publicly available repository for community agreed methods and reviewed by a community of experts) which allow users to find values for uncertainty, precision, accuracy, etc within different laboratories and methods.

7.5. General Description of Key Capabilities

To be focused on actionable recommendations for research infrastructure and capability requirements

7.5.1. Digital Infrastructure

Increase model and statistical capability. These capabilities can be leveraged using big data analytics including integrated, diverse data sources; predictive models, including hydrodynamic modelling, such as pollution dispersion and ecosystem impact models; and statistical risk models and/or Probabilistic Risk Assessment (PRA) to assess the probability and potential impact of pollution events.

Develop AI and observation from space for rapid/large area surveys. Machine learning algorithms, particularly Convolutional Neural Networks (CNNs), can analyse satellite images (and drones equipped with a high-resolution camera) to detect oil spills, plastic waste, and other pollutants in the ocean. AI-powered geospatial analysis tools can create maps of pollution distribution, helping to identify pollution sources.

7.5.2. Observational Infrastructure

Improve and increase availability of equipment and technology for *in situ* analyses to test the multi-stressor impacts of combinations of contaminants. This should include multi-stressor and long-term experiment facilities, statistic and dynamic marine platforms, and low-power, high-sensitivity autonomous sensors and samplers (i.e. chemical sensors, biosensors, AUVs and ROVs, Diffusive passive sampling device such as Gradients in Thin films (DGT) or Semipermeable Membrane Devices (SPMDs), active samplers and Lab-on-a-Chip (LOC) Devices).

Creating advanced waste treatment. This also includes recycling technologies and innovative methods for cleaning up existing marine pollution.

7.5.3. People, Skills and Partnerships

Education and awareness raising, this includes opportunities for cooperative and intersectional analytical and social science solutions such as the use of citizen science to increase sample collection and data generation while increasing awareness.

Engage more positively with industry and other stakeholders. Scientists and industry can collaborate on R&D projects (to develop new technologies and methods for pollution control, waste management, and sustainable production processes) and establish industry-scientist advisory panels to provide guidance on pollution reduction strategies. Encourage industries to make environmental data publicly available, allowing scientists to analyse and provide insights for improvement and collaborate to promote policies and regulations that support sustainable industrial practices and pollution reduction.

Foster collaborations and knowledge sharing between facilities to reduce competition for funding and keep broad capability of community and synergise efforts. Support interdisciplinary scientific field studies and collaborations.

Increasing dialogue around management strategy to prevent, mitigate, reduce, and regulate. This will require an integrated approach that combines regulatory frameworks, technological advancements, industry best practices, and community engagement.

7A. Annex

7A.1. Initiatives identified

Some initiatives have been identified. A list of those mentioned:

- Ocean Decade, United Nations has 10 Challenges, Challenge 1: Understand and beat marine pollution. A few months ago, 10 White papers were released, and 1 was specific for Pollution.
- Back to Blue includes several initiatives for pollutants.
- World Health Organization (WHO) policy brief.
- UK 5-year action plan for AMR
- EU Marine Strategy Framework Directive (MSFD)
- Water Framework Directive (WFD) England and Wales
- Nutrient Pollution – Global Action Network (NP-GAN)
- Harmful Algae Bloom Solutions (HAB-S) Programme
- Intergovernmental Negotiating Committee on Plastic Pollution
- OSPAR
- MERMAN is a national database which holds and provides access to data collected under the Clean Safe Seas Environmental Monitoring Programme (CSEMP) — formerly the National Marine Monitoring Programme (NMMP).
- QUASIMEME catalogue covers various programmes of contaminants in seawater, biota and marine sediment.
- Offshore Chemical Notification Scheme (OCNS) applies to chemicals that are intended for use and discharge in the exploration, exploitation and associated offshore processing of petroleum in the UK and Netherlands.
- Marine Natural Capital and Ecosystem Assessment Programme (mNCEA) is Defra's flagship 3-year research and development programme that will provide a robust evidence base, suite of tools and a framework where ecological, societal, and economic information is brought together in a holistic way.

7A.2. List of Pollutants identified

The list of pollutants suggested in the B2B Roadmap was used as a starting point. Experts agreed on the list, but some new groups were also recommended (see Table below).

Group of Pollutants	**Comments**	**Phenomena to Capture, Temporal and Spatial Scales of the Phenomena**	**Current Observing Networks, Maturity, Spatial and Temporal Scale Covered**	**Future Observing Capacity**
BACK TO BLUE ROADMAP				
Persistent bio-accumulating and toxic compounds (PBTs)	Those that accumulate in the environment over long periods. This includes persistent organic pollutants (POPs), per- and polyfluoroalkyl substances (PFAS, sometimes called “forever chemicals”), and some pesticides.	Main processes: bioavailability, bioaccumulation (biomagnification), biological role and toxicity of PBTs: -Effect of route of transport on PBT bioavailability -Factors affecting the bioaccumulation of PBTs -Toxicity of PBTs -Assessment of PBTs toxicity and bioavailability from polluted marine sediments -Biological role of PBTs and human health hazards. -Cumulative impact with other pollutants	-Discrete samples: water, air, biota, sediments. From local (monitoring programmes) to global coverage (e.g. Caribbean Coastal Pollution Project (CCPP) to study POPs in mammals and ecological and human influence) -UK Marine Strategy for sediments[1], water and biota: following OSPAR Convention and Water Framework Directive (WFD).	-Autonomous platforms equipped with in-situ sensors/samplers. -Ecotoxicology infrastructures -In-situ incubators for sediment-water interactions. -In-situ samplers/sensors for sediment samples.
Heavy metals	Including mercury, lead, copper and cadmium.	Enter the marine environment from a number of natural, agricultural, and industrial processes, via long-range	-Discrete samples: water, air, biota, sediments. From local (monitoring programmes) to global coverage (e.g. GEOTRACES)	-Autonomous platforms equipped with in-situ sensors/samplers. -Ecotoxicology infrastructures -In-situ incubators for sediment-sea interactions.

[1] https://moat.cefas.co.uk/pressures-from-human-activities/contaminants/

		transport by air, riverine input, or run-off from land. Main processes: bioavailability, bioaccumulation, biological role and toxicity of heavy metals: -Effect of route of transport on metal bioavailability -Factors affecting the bioaccumulation of heavy metals -Toxicity of heavy metals -Assessment of heavy metal toxicity and bioavailability from polluted marine sediments -Biological role of heavy metals and human health hazards -Cumulative impact with other pollutants	-UK Marine Strategy for sediments, water and biota: following OSPAR Convention and Water Framework Directive (WFD). -Multidisciplinary research projects air-sea interactions (SOLAS)	-In-situ samplers/sensors for sediment samples.
Nutrients	Fertilisers and organic matter, including human and animal waste, that lead to eutrophication, where algal blooms consume so much oxygen from	GOOS EOV: -Ventilation; annual to decadal; 1000-3000 km. -Primary production; seasonal to decadal; Coastal (0.1-100 km), Open-ocean (100-1000 km).	GOOS EOV: -Ship-based underway observations; Pilot; Horizontal coverage (surface); weekly to decadal -Ship-based repeat hydrography; mature;	GOOS EOV: -Underwater and surface vehicles -Moored fixed-points observations

	the water that other sea life dies.	-Eutrophication; sub-weekly to decadal; Coastal (0.1-100 km).	Horizontal and vertical cover; decadal -Ship-based Fixed-point observatories; Mature; Horizontal cover (local); weekly to decadal -Profiling floats; pilot; Horizontal cover (Global) -Profiling floats; Pilot; Horizontal cover (global)	
Plastics	Including solid plastic waste as well as micro- and nanoplastics. Plastics are a chemical pollutant in their own right and can pick up and transport other chemicals long distances.	-Ecotoxicity impact of plastic in future multi-stress marine environment (including other pollutants) under short- and long-term exposure -Cumulative impact with other pollutants -Identify behaviours and fate of plastics exposed to environmental change/weathering -Vertical residence time of plastics and from sea-surface to seabed -Increase the number of monitoring sites globally, - Monitor the transfer of plastics through the marine	At global scale GOOS, under the Intergovernmental Oceanographic Commission (IOC) of UNESCO, is working to include marine plastic pollution as an Essential Ocean Variable (EOV). Still developing, but it aims to standardize methods for data collection and provide a coordinated approach to global plastic monitoring, GPML, led by the United Nations Environment Programme (UNEP), is a voluntary partnership and Ocean Conservancy, the ICC is the largest volunteer efforts to collect and document	-Controlled multi-stress mesocosms platform -In situ oceanic plastic degradation/behaviour platform (Moored and drifting float) -Globally accessible plastic polymer spectral library with -Enhance the use of AI and machine learning algorithms for the automated detection, classification, and quantification of plastic pollution from imagery and sensor data -Underwater vehicles (AUVs), drones, and gliders equipped with sensors and cameras to conduct large-scale and fine-scale surveys of marine plastic -In situ sensors and smart buoy to monitoring in continuous micro and nano plastic presence

		food web and assess potential impacts on human health	marine litter, including plastics, from coastlines. Regional scale such as NOAA and OSPAR provide continuous monitoring	-Establish global standards and protocols for marine plastic monitoring, including sampling methods, data processing, and reporting
Pharmaceuticals	Including medications for humans and animals, with antibiotics a central concern given their overuse or misuse.	-Sources: Sewage effluent, aquaculture, Animal husbandry and horticulture, Waste disposal. -Processes[2]: pharmaceuticals and their metabolites can undergo biotic and abiotic transformation (degradation) and sorb to suspended particulate matter (SPM) and sediments, and in some cases accumulate in the tissues of aquatic organisms. This will be affected by physicochemical conditions of the environment. -Antimicrobial resistance -Seasonal trends, sediment concentration, marine ecotoxicology, factors influencing concentration.	-Discrete samples: water, biota, sediments. -Sewage discharge legislation: Annex IV of MARPOL 73/78 ships -Water Framework Directive[3] (WFD; Directive 2000/60/EC) covers both freshwaters and transitional waters (the estuarine and coastal area up to one nautical mile, or 1.85 km, from the shore). Two hormones (17α-ethinyloestradiol and 17β-oestradiol) and diclofenac have been placed on a watch list for emerging pollutants under the WFD.	- Improve monitoring of dissolved and particulate fraction of relevant pharmaceuticals and degradation products. - Improve data for the accumulation of other classes of pharmaceuticals, their metabolites and transformation products in marine organisms -Improve coverage data

[2] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4213585/
[3] https://www.legislation.gov.uk/uksi/2017/407/contents

Radioactivity	Including recent contamination, the historical dumping of radioactive waste, and radiation from natural sources.	Nuclear waste comes from a variety of sources, such as nuclear power plants, nuclear waste recycling plants, nuclear-powered vessels and weapons testing, hospitals, scientific research centres, and nuclear weapons facilities, as well as from events such as nuclear spills, the sinking of a nuclear-powered submarine, or leakage from sealed waste. But there is also natural radiation. Processes: -Effects of nuclear waste: genetic mutations, development or reproductive changes, cancer, decreased lifespan, and death. -Transport, fate and impact	Discrete samples of biota, water and sediments: C-137 UK organisations carry out monitoring programmes to provide an independent assessment of radiation levels in the environment. (UK strategy for radioactive discharges: 2018 review of the 2009 strategy) OSPAR Recommendation 2018/01 on Radioactive Discharges[4] and North-East Atlantic Environment Strategy (NEAES) 2030[5].	Measurement of radioactivity in the environment - more accurate and rapid radiometric methods. Potentially nuclear fusion could place a renewed emphasis on tritium. Given concerns about tritium releases from Fukushima and a new focus on tritium releases from nuclear sites worldwide, tritium may become of more interest, though of course it is currently routinely measured as part of site environmental programmes. More emphasis on elements or analogues for environmental mobility of very long-lived elements in nuclear waste. More emphasis on naturally occurring radioactive materials (NORM) waste. There is significant historical and ongoing NORM waste from e.g. oil and gas extraction. Model developments - this is a mature field and there has already been a lot of model development and process understanding. I see more importance in application and testing of models. Continuing work on models for

[4] https://www.ospar.org/documents?d=38954
[5] https://www.ospar.org/documents?v=46337

				nuclear waste disposal, particularly if a UK waste disposal site is chosen. Ecotoxicology/radioecology - there has been and will be a lot of work on environmental impacts of radioactive pollution. Most of this work is not properly hypothesis driven nor are the current very vague hypotheses properly tested. I think progress in this is likely to be limited unless key issues (lack of testable hypotheses, lack of attempts to reproduce findings, problems with determining if radiation is the causal factor in apparent effects seen in the environment) are properly addressed. Modelling capabilities are important - these need to be informed by in situ observation. Statistical capability is important. Models have been developed for regulation of routine discharges, for accident scenarios and for geological disposal of nuclear waste. Ongoing work is needed to ensure these are robust and that there is sufficient capability for future needs. Time scales range up to say 100,000 years for geological waste disposal.

Oil	Including the toxic chemicals used to clean up spills.	Oil spills. Main sources are shipping, port and harbours, and offshore oil and gas industries	-Discrete samples: water, air, biota, sediments. From local (monitoring programmes) to global coverage (e.g. Caribbean Coastal Pollution Project (CCPP) to study POPs in mammals and it's ecological and human's influence) -UK Marine strategy for sediments, water and biota: following OSPAR Convention and Water Framework directive (WFD). -Sensors installed in moorings, mobile platforms and satellites. -UK has a well-developed and exercised process of response, including measures set out in the UK National Contingency Plan. UK Government is fully engaged with European and international partners across a range of groups and initiatives relating to the prevention of spills including	-For satellite: Need for a valid database with spills and lookalikes for algorithms improvement; new "multi or hyper" band radar sensors to eliminate the detection errors; AI to process large amount of data (Topouzelis, and Singha, 2016). -New type of in situ measurements: low-cost buoys with sensors measuring the type of oil and its chemical composition; small AUV/UAVs for large area monitoring in high resolution.

			those presided over by OSPAR, International Maritime Organization[6] and European Maritime Safety Agency[7].	
Household and consumer chemicals *The list of chemicals in the average home is long, featuring items like solvents and household cleaners, mould removers, laundry products, detergents, bleach, furniture polish, air fresheners, paints and varnishes, poisons (insecticides, for example) and batteries.*	Many cleaning products contain toxic chemicals, as do numerous cosmetics (Benzophenone[8]), shower gels and sunscreens.	Many cosmetics, shower gels, deodorants, shampoo and sunscreens, for example, contain benzophenone or its derivatives oxybenzone130 and dioxybenzone,131 which are used for their ability to absorb UV-A and UV-B light. Oxybenzone is toxic to aquatic life and has long-lasting effects,132 as are other substances added to some sunscreens such as octinoxate, 4-methylbenzylidene camphor and butylparaben.	-Discrete samples for some research studies. -Some components are banned, like Benzophenone is cosmetic products.	We need more studies to understand: -The impact of these products in marine life. -To fill major data gaps regarding the trends of emerging contaminants in freshwater and marine environments as well as their impact on aquatic wildlife in the UK. -Understand the impact when it's combined with many other stressors such as climate change and habitat loss.
Pseudo-persistent chemicals *For UNEP, a half-life longer than 60*	These would dissipate relatively quickly in the aquatic environment, except that their	Main processes: bioavailability, bioaccumulation	-Discrete samples: water, air, biota, sediments. From local (monitoring programmes) to global coverage.	More research[9] is needed to see how long chemicals persist in the environment versus their supposed

[6] http://www.imo.org/en/About/Pages/Default.aspx
[7] http://www.emsa.europa.eu/
[8] https://www.legislation.gov.uk/eur/2009/1223/annex/II
[9] https://backtoblueinitiative.com/wp-content/uploads/2022/11/Chemical-pollutants-of-major-concern.pdf

days in water falls into the persistent category. Stockholm Convention and other regulatory lists of hazardous chemicals.	concentrations keep rising because they are so prevalent in products.	(biomagnification), biological role and toxicity: -Effect of route of transport on chemicals bioavailability -Factors affecting the bioaccumulation of chemicals -Toxicity -Assessment of chemicals toxicity and bioavailability from polluted marine sediments -Biological role of chemicals and human health hazards. -Cumulative impact with other pollutants		persistence in a laboratory setting, not least as persistence is one of the key criteria for inclusion in the Stockholm Convention and other regulatory lists of hazardous chemicals.
Other chemicals	Including a wide variety of the approximately 300,000 chemicals in use, most of whose effects on the environment and human health are unknown.	Main processes: bioavailability, bioaccumulation (biomagnification), biological role and toxicity: -Effect of route of transport on chemicals bioavailability -Factors affecting the bioaccumulation of chemicals -Toxicity -Assessment of chemicals toxicity and bioavailability from polluted marine sediments	-Discrete samples: water, air, biota, sediments. From local (monitoring programmes) to global coverage.	-Autonomous platforms equipped within situ sensors/samplers. -Ecotoxicology infrastructures -In situ incubators for sediment-sea interactions. -In situ samplers/sensors for sediment samples. -Needs more sample screening to detect new components. -Store samples for future experiments

		-Biological role of chemicals and human health hazards. -Cumulative impact with other pollutants		
INPUT FROM MEETINGS				
Invasive non-native species (INNS)	Including species that can alter marine ecosystems.	-Identify source, Population Growth and Spread -Ecological Impact (short term versus long term) which includes Displacement of Native, Species, Genetic Pollution and Habitat Modification	-Global Ballast Water Information Clearinghouse (GBWIC) is an established network within the International Maritime Organization (IMO) and the Global Invasive Species Programme (GISP). It was developed to monitor and manage the spread of invasive species through ballast water. -Global Invasive Species Database (GISD) has a Section managed by the IUCN's Invasive Species Specialist Group (ISSG) -Alien Species Information Network (EASIN) is an integrated system within Europe, created by the European Commission. This network has a marine	-Remote Sensing and Satellite Technology with High-Resolution Imagery and Spectral Sensing Monitoring large-scale marine habitats and coastal zones for signs of invasive species and tracking the movement and spread of invasive species in real time -Environmental DNA (eDNA) Technology including High-Sensitivity Detection: of low concentrations and use of Portable Devices for field-based testing and faster results. -Artificial Intelligence (AI) and Machine Learning for the prediction of invasive species spread and Automated Image Analysis of remote sensing imagery and underwater videos/photos. -Real-Time-Rapid Response Systems-sensors

			component that focus on monitoring invasive species in European marine environments. -The Marine Aliens Project, supported by the UK government and various academic institutions, is a mature network focused on monitoring marine invasive species in the United Kingdom. Covers UK coastal and marine environments. Involves both historical analysis and continuous monitoring.	
Noise	Ocean sound, including underwater noise pollution.	-Enhancing ability to track and manage marine noise pollution on various scales -Continuous Underwater Noise generate in the ocean from shipping traffic or other offshore activity and Short, high-intensity noise events that occur sporadically such as underwater explosions, pile driving, -Impact on marine life and behaviour of different type of	-Noise impacts on specific species, such as whales using arrays of hydrophones and classification of sound sources, including both natural and anthropogenic noise. -Standardized methods and protocols for global data collection -Global Networks include International Quiet Ocean Experiment and Ocean	-Real-time data collection and AI-driven analysis Implement satellite-linked buoys equipped with hydrophones -Utilize IoT technology to create a network of interconnected hydrophones -Invest in the development of low-cost, high-resolution hydrophones that can be widely deployed, including in citizen science projects

		Noice i.e. vibratory versus tonal noise and/or any Noise that directly interferes with the sounds produced by marine organisms.	Sound EOV. Same Regional networks operate continuously, with fixed hydrophone arrays (IOOS [US], ONC [Canada]).	
Light level	Including coastal darkening, CDOM, artificial light at night (ALAN).	-Quantify the intensity and distribution and trend of ALAN in marine environments -Highlighting hotspots of light pollution and identifying areas most at risk of ecological disruption Quantify the effect of Impact on Direct glare, light trespass i.e. passing ship's; Skyglow leading temporal disruption i.e. Nightly increase in sky brightness over coastal cities, disruption of daily life cycle in marine ecosystem; Seasonal variations in skyglow (especially during the winter month) during winter months, bioluminescence suppression.	-Global network such as GOOS and MBON are well-established for broader ocean monitoring but are only beginning to consider light pollution as a factor. -The International Dark-Sky Association plays a key role in the awareness and monitoring of light pollution, which indirectly affects coastal marine environments.	-Existing marine observing networks need better integration of light pollution metric and define standard methods. For example, Satellite observations, such as NOAA Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band, provide global coverage of light pollution, including in marine areas. VIIRS is particularly useful in monitoring light pollution in coastal regions, where human settlements, industrial activities, and tourism contribute to ALAN. VIIRS can be also used to track light pollution from ships, which can be a significant source of ALAN, -Drones equipped with cameras or sensors to monitor light pollution to provide fine spatial data. -All-Sky Cameras (equipped with fisheye lenses) to provide continuous and quantitative data

Biological	Includes faecal bacteria, pathogens, endocrine disrupters and antimicrobial resistant bacteria.	-Presence and Concentration; Spread and Transmission; Co-Occurrence with Antibiotics (in the case of AMRs), Bioaccumulation (for EDCs), Faecal Indicator Bacteria (FIB) Concentration (in the case of Faecal contamination) -Event base (i.e. suddenly spills or discharge Short-Term (Daily to Weekly) for phenomena that fluctuate rapidly, like faecal contamination after rainfall, pathogen outbreaks, plus Long-Term (Monthly to Yearly) for understanding i.e. trends and bioaccumulation. -Local (Near sources of pollution) versus global spatial scale where pollutants can be transported across large distances	There is ongoing need for integration and expansion, particularly in the context of environmental AMR monitoring and emerging contaminants like endocrine disruptors. Faecal materials are better developed at local and regional scale. Overall monitoring endocrine disruptors is less mature compared to traditional pollutants. Environmental Monitoring and Assessment Programs: Agencies like the EPA, EEA, has a specific monitoring programs to track endocrine disruptors like bisphenol phthalates, and pesticides while international research consortia (such as EU's NORMAN Network) are assessing the presence of emerging contaminants, including endocrine disruptors	The future observing capacity for marine biological pollution, including faecal material, endocrine disruptors, pathogens, and antimicrobial-resistant bacteria, is expected to advance significantly due to innovations in technology, data integration, and global collaboration. Here's what the future might hold in these areas: -Faecal material real-time monitoring with advanced sensors stationed at key locations such as coastal outflows and river mouths, and marine recreational spot; -Satellite-based remote sensing combined to enhance the detection and mapping of faecal contamination over larger areas, where combination with AI algorithm could predict contamination events. Development of portable, user-friendly monitoring kits could empower communities improving spatial coverage. -Endocrine Disruptors-Advanced in analytical technique such as mass spectrometry, to screen for a broad spectrum of endocrine disruptors in marine environments. Development of

				in situ bioassays that can assess the biological impact of EDCs directly in the marine environment. -Overall Real-time monitoring, advanced analytical techniques, AI-driven predictions, and integrated One Health approaches will enable more accurate monitoring of faecal material, endocrine disruptors, pathogens, and antimicrobial-resistant bacteria.

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7A.3. Contributors

The list includes all experts that have contributed to this report by either answering the questionnaire, sending their inputs by email or joining the roadshows organised (names are listed by alphabetical order):

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Emily Rowlands	British Antarctic Survey (BAS)
Emma Ransome	Imperial College London
Gareth Roberts	Imperial College London
Geslaine Rafaela Lemos Goncalves	Scottish Association for Marine Science (SAMS)
Guy Woodward	Imperial College London
Hannah Whitby	University of Liverpool
Helena Reinardy	Scottish Association for Marine Science (SAMS)
Jason Weeks	Joint Nature Conservation Committee (JNCC)
Jim Smith	University of Portsmouth
Joe Penhaul Smith	Sustainable Sailing Ltd
Josie Russell	Centre for Environment, Fisheries and Aquaculture Science (CEFAS)
Justin Dunning	Chelsea Technologies
Leon Barron	Imperial College London
Lonneke Goddijn-Murphy	ERI, University of the Highlands and Islands
Lucy Woodall	University of Exeter
Mark Fitzsimons	University of Plymouth
Matt Cole	Plymouth Marine Laboratory (PML)

Michelle Devlin	Centre for Environment, Fisheries and Aquaculture Science (CEFAS)
Neil James	Environmental Research Institute, University of the Highlands and Islands
Nienke Van Geel	Scottish Association for Marine Science (SAMS)
Nikolet Kostur	King's College London
Rachel Jones	Zoological Society of London
Richard Lampitt	National Oceanography Centre (NOC)
Yevgeny Aksenov	National Oceanography Centre (NOC)

7A.4. Cross-cutting ideas

There are some cross-cutting areas or activities we have identified that this challenge will benefit from working together with others. Some examples:

- Having a sampling strategy where we combined efforts to reduce labour time, ship time and cost.
- Holistic approach when organising field camping and studies. Pollutants is not an isolated problem; it requires other variables to really understand how other environmental and societal variables are connected and how each variable affect the other.
- Combined efforts when engaging with industry, society and government to reduce stakeholders' fatigue and avoid duplication of efforts.

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[i] https://uk.linkedin.com/company/economist-impact?trk=public_post-text
[ii] https://jp.linkedin.com/company/the-nippon-foundation?trk=public_post-text
[iii] https://backtoblueinitiative.com/wp-content/uploads/2024/03/Back-to-Blue-Roadmap-for-Action-on-Ocean-Pollution.pdf
[iv] https://fr.linkedin.com/company/ioc-unesco?trk=public_post-texthttps://fr.linkedin.com/company/ioc-unesco?trk=public_post-text
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[vi] https://oceandecade.org/vision-2030/
[vii] https://oceandecade.org/challenges/