Section 4

Subchapter 6E

Pollution

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Key points

- Chemicals and other materials from land-based sources continue to impact ocean ecosystems.
- There has been a decline in mercury emissions and precipitation, along with reductions in emissions to air of some organic compounds, in certain regions.
- Growing demand for non-carbon electricity has resulted in an increased reliance on nuclear power, which is likely to lead to higher radioactive discharges.
- Persistent organic pollutants (POPs) continue to impact all ocean regions, including polar regions and the deep sea, as well as coastal marine ecosystems.
- Toxicity studies indicate that pharmaceuticals and personal care products (PPCPs) have significant adverse effects on marine organisms, including behavioural changes in fish, invertebrates and algae.
- Global plastic waste emissions continue to rise, with substantial leakage due to mismanaged waste, microplastic abrasion and loss, littering and marine activities. These plastics, especially microplastics, impact all marine ecosystems, with over 4,000 species affected.

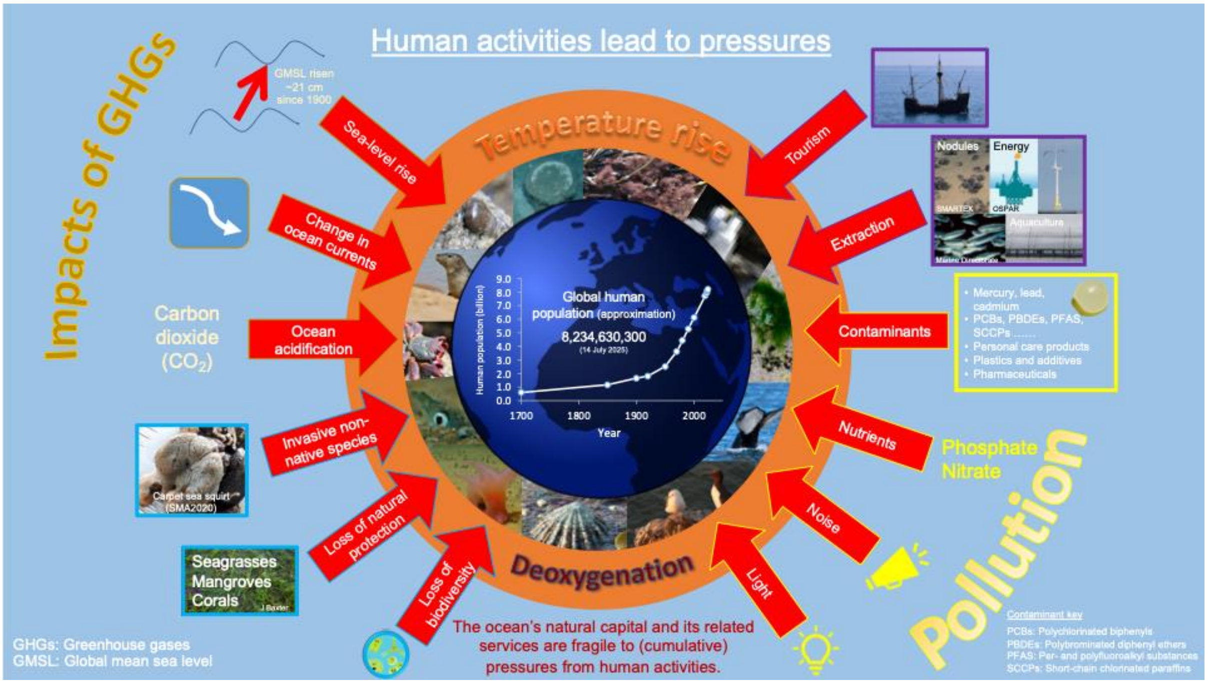
1. Introduction

Human activities generate multiple pollutants, including pharmaceuticals, heavy metals, organic compounds, radioactive materials, plastics and plastics additives, sediments, nutrients, pathogens, energy (heat, light and noise) and numerous other contaminants of emerging concern. The focus of the present subchapter is initially inputs of heavy metals and selected contaminants from the atmosphere and rivers. This is followed by a more in-depth discussion of the concentrations and effects of POPs, pharmaceuticals, personal care products, plastics and plastics additives and radioisotopes. Many of these compounds and materials ultimately reach the ocean through atmospheric transfer and deposition, general land run-off, rivers, storm overflows and sea-based activities. These pollutants may subsequently be transported more widely by ocean currents. As a result, marine biota are exposed to numerous chemicals, many of which have physiological effects. Alongside biodiversity loss and rising concentrations of greenhouse gases, such as carbon dioxide (CO_2), methane and nitrous oxide, pollutants further intensify an already precarious multiple stressor scenario for marine ecosystems (see figure I).

The present subchapter provides an update to the information contained in the second *World Ocean Assessment* on the concentrations and consequences of POPs, plastic products and additives, pharmaceuticals, personal care products and radioisotopes on the ocean and the marine organisms that live in, on or near the ocean. This is coupled with recent developments in the understanding of the atmospheric inputs of a range of chemicals to the ocean. While the materials and chemicals covered are similar to those described in the second *Assessment*, greater emphasis is placed on per and polyfluoroalkyl substances (PFASs), and PPCPs are discussed in greater depth.

Figure I

Pressures from and of human activity on marine ecosystems



Source: Prepared by the writing team. World population data from Worldometer. Images of polymetallic nodules and the "Barbie Pig" are courtesy of the National Oceanography Centre and the Trustees of the Natural History Museum of the United Kingdom, with acknowledgement to the Natural Environment Research Council's Seabed Mining and Resilience to Experimental Impact (SMARTEX) project. Images of the sand eel and deep-sea sponge are courtesy of the Scottish Marine Directorate.

Note: The presence of pollutants further exacerbates an already precarious multiple stressor situation for marine ecosystems.

Abbreviation: SMA2020*, Scotland's Marine Assessment 2020.*

2. Recent developments in atmospheric and riverine inputs

Key points

- Both atmospheric deposition and riverine inputs remain important pathways through which contaminants, including plastics, reach the ocean.
- Nevertheless, there has been a decline in air emissions of heavy metals and some legacy POPs from western Europe.

Contaminants continue to be distributed globally

Long-range atmospheric transport continues to be a key process by which pollutants move around the planet. As a result, pollutants impact marine organisms a considerable distance from their sources of emission. Long-range atmospheric transport is a key driver behind pollutants that are detected in the polar regions and the deep ocean, including the Mariana Trench (Dasgupta and others, 2018). In the deep ocean, ocean currents are another key driver. Chlorinated paraffins have been detected in deep-sea cold seep ecosystems, where they have been bioaccumulated by deep-sea mussels (Lyu and others, 2023). In deep-sea sediments from the western Pacific Ocean, concentrations of some POPs, including polychlorinated biphenyls (PCBs) and dicofol, were low or the compounds were not detected. In the same samples, however, polycyclic aromatic hydrocarbons (PAHs) were detected at concentrations between 5.2 and 24.5 nanograms per gram (ng/g) dry weight. Biomass and coal combustion have been identified as the predominant sources of PAHs, which indicates atmospheric deposition (Ge and others, 2021).

Per- and polyfluoroalkyl substances

Interest in per- and polyfluoroalkyl substances (PFASs) has grown in recent years. More details about concentrations and impacts of PFASs can be found under “Persistent organic pollutants” below. Determining the source of these compounds is important. An analysis of an ice core from Devon Island, Nunavut, in northern Canada revealed continuous and increasing deposition of perfluoroalkyl carboxylic acids (PFCAs) and perfluoroalkyl sulfonic acids (PFSAs) over the period 1977–2015. North American and Eurasian emission sources, particularly sources in Continental Asia, were large contributors (Pickard and others, 2018).

In some cases, riverine inputs remain critical. For example, the riverine input of perfluorooctanesulfonic acid (PFOS) to the Baltic Sea exceeds atmospheric input by a factor of three. In other cases, such as with perfluorooctanoic acid (PFOA) and other PFCAs, atmospheric deposition makes a higher contribution to the total inputs to the Baltic Sea (Johansson and Undeman, 2020). Potential sources of the loading of PFOS and other PFASs in rivers in the Baltic Sea region include discharges from wastewater treatment plants, atmospheric deposition to catchment areas and run-off from contaminated sites (Baltic Marine Environment Protection Commission (HELCOM), 2020). The relative contribution probably varies from river to river.

Atmospheric deposition can be dry or wet. In their study on four perfluoroalkyl acids (PFOS, PFOA, perfluorohexanesulfonic acid (PFHxS), and perfluorononanoic acid (PFNA)), Cousins and others (2022) concluded that:

- Levels of PFOA and PFOS in rainwater often greatly exceed the lifetime drinking water health advisory levels established by the Environmental Protection Agency of the United States.
- The sum of those four perfluoroalkyl acids in rainwater is often above Danish drinking water limit values.
- Levels of PFOS in rainwater are often above the European Union environmental quality standard for inland surface waters.
- Atmospheric deposition leads to contamination of global soils.

Pharmaceuticals

Mass consumption of certain pharmaceuticals has led to a greater concentration of pharmaceutical residues in aquatic environments and river discharges. Septic tanks are also a pathway for emerging contaminants, including different analgesics, antihistamines, antidepressants, betablockers and the antidiabetic drug metformin, entering the aquatic environment (Wilschnak and others, 2024).

Declines in emissions and deposition of contaminants are happening

Humans have become acutely aware of the risks associated with both organic and inorganic contaminants. Actions have been and continue to be taken to limit emissions and discharges of contaminants. These actions are having an impact (see box 1).

Box 1

Case study: declines in emissions and deposition of heavy metals and selected organic contaminants

Mercury in air, precipitation and emissions to the air from European Union countries decreased by 1.3%, 3.0% and 3.2% annually, respectively, over the period 2010–2022 (Gauss and others, 2024). Declines during that period were higher than those recorded during the period 2000–2010. European emissions declined faster than concentration levels in air, showing the influence of long-range atmospheric transport on mercury air concentration.

In the Western region of the European Monitoring and Evaluation Programme (EMEP), which covers western Europe, emissions to air of cadmium, mercury and lead declined over the period 2000–2022, as did emissions to air of polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), hexachlorobenzene (HCB) polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDD/F). In the Eastern region, which covers Eastern Europe, the Caucasus and Central Asia, emission trends are not completely evident, mainly due to incomplete reporting by major emitting countries.

An example of a decrease in deposition was noted for the Baltic Sea where the deposition of mercury, lead, cadmium, and benzo[a]pyrene has decreased steadily since 1990 (Gauss and others, 2024).

3. Persistent organic pollutants

Key points

- POPs remain a global problem due to their persistence, bioaccumulation and health risks.
- POPs, including emerging ones such as PFASs, and replacement chemicals, including polyhalogenated carbazoles (PHCZs), are gaining increasing attention because their environmental and public health impact continues to be exacerbated by inadequate waste management, climate change-related remobilization of POPs that have been trapped in water, ice sediments and soil for decades, and inconsistent global enforcement of international agreements despite international efforts to eliminate their sources.
- Although POPs are yet another anthropogenic pressure on the ocean, adding to the stress on biological systems, there is some indication that concentrations of some legacy compounds are decreasing.

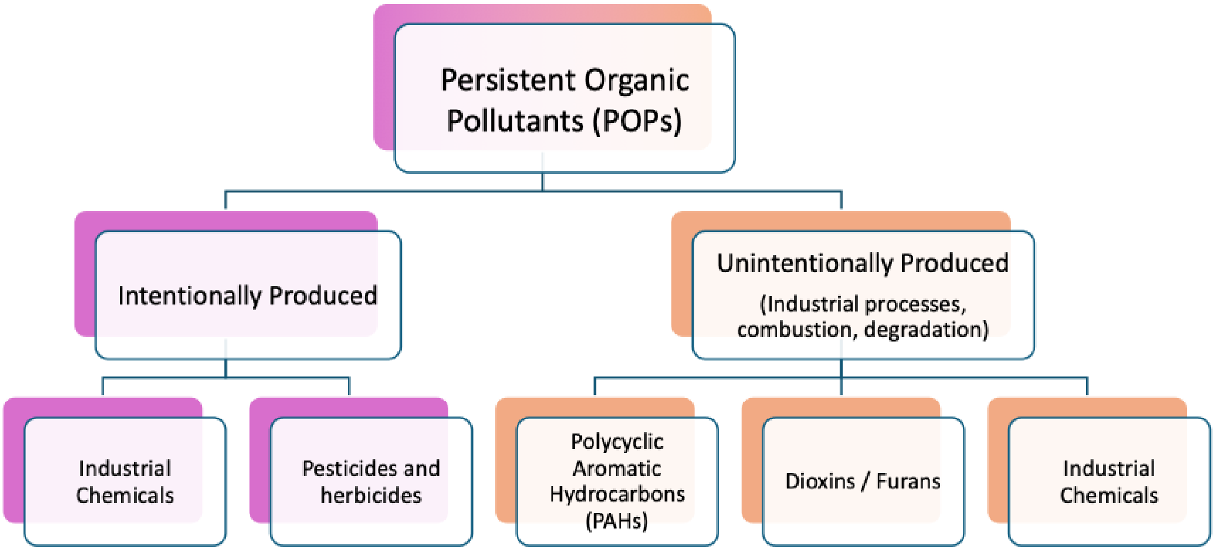
Introduction

Many chemicals have been produced to improve human lives. These chemicals are discharged and emitted into the environment and continue to be one of the main stressors on marine ecosystems.

POPs, which are generally hydrocarbons that are halogenated (containing fluorine, chlorine or bromine) (Guo and others, 2019), may be produced intentionally or unintentionally (see figure II). They include PCBs (209 individual congeners), polybrominated diphenyl ethers (PBDEs) and PFASs (see table 1). Although the manufacture of some POPs is now banned, such bans entered into effect only after significant quantities had been manufactured and used. For example, 8,896 kilotons of hexachlorocyclohexanes (HCHs) were manufactured before being banned (Li and others, 2023).

Figure II

The range of persistent organic pollutants



Source: Prepared by the writing team.

Note: Industrial chemicals are produced both intentionally and unintentionally. PCBs and polychlorinated naphthalenes (PCNs) are produced unintentionally during the production of paints and dyes (Hu and Hornbuckle, 2009; Hannah and others, 2022) and at nonferrous metallurgical facilities (Klimczak and others, 2023). Polychlorinated diphenyl ethers (PCDEs) are by-products of the synthesis of commercial chlorophenols (Wu and others, 2023). POPs, including PAHs, may also be produced during combustion. Although PAHs are not covered by the Stockholm Convention, they are included in the figure because they are classified as POPs.

POPs continue to be manufactured and reach the ocean through a variety of pathways (see figure III). However, these halogenated compounds persist in the environment and are bioaccumulated, especially in higher trophic levels (see figure IV). This means that as humans introduce new chemicals, further problems arise. In addition, these chemicals are dispersed by ocean currents and atmospheric winds resulting in them being found around the globe (see figure III).

Table 1

Persistent organic pollutants

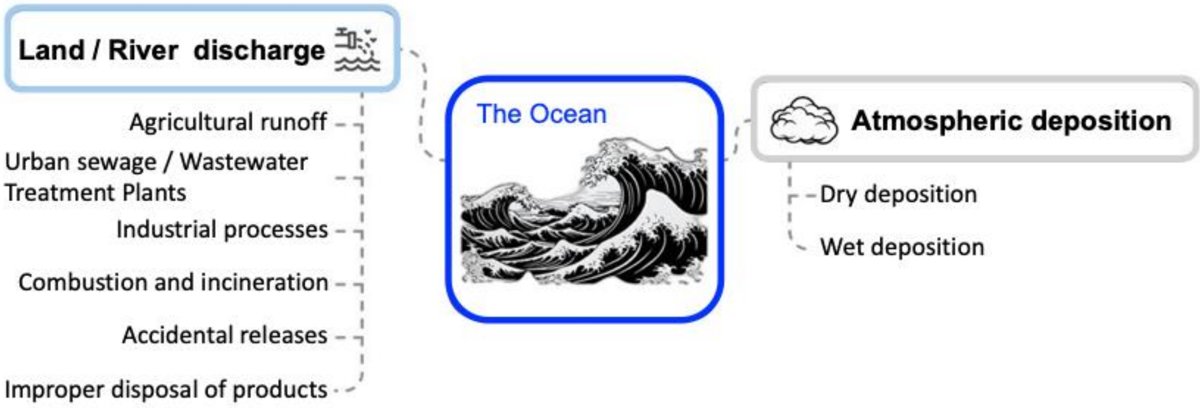
Chemical Group	Abbreviation	Chemical Group	Abbreviation
Polychlorinated biphenyls	PCBs	Per- and Polyfluoroalkyl substances	PFAS
Polychlorinated diphenyl ethers	PCDEs	Perfluoroalkyl sulfonic acids	PFSAs
Polychlorinated naphthalenes	PCNs	Perfluoroalkyl carboxylic acids	PFCAs
Polybrominated diphenyl ethers	PBDEs	Organochlorinated pesticides	OCPs
Polybrominated biphenyls	PBBs	**Individual Chemical**	**Abbreviation**
Polychlorinated dibenzo-p-dioxins	PCDD	Perfluorooctanesulfonic acid	PFOS
Polychlorinated dibenzofurans	PCDF	Perfluorohexane sulfonic acid	PFHxS
Polyhalogenated carbazoles	PHCZs	Perfluorooctanoic acid	PFOA
Toxaphene	Toxaphene	Perfluoroheptanoic acid	PFHpA
Short-chain chlorinated paraffins	SCCPs	Hexachlorobenzene	HCB
Hexachlorcyclohexane	HCH	Dichlorodiphenyltrichloroethane	DDT

Source: Prepared by the writing team.

Note: PHCZs and PFHpA are not listed in the Stockholm Convention on Persistent Organic Pollutants. The Stockholm Convention lists the following groups of PFASs: PFOS, its salts and perfluorooctane sulfonyl fluoride (PFOSF) (including all PFOS precursors); PFOA, its salts and PFOA-related compounds (including all PFOA precursors); PFHxS, its salts and PFHxS-related compounds (including all PFHxS precursors); and long-chain PFCAs, their salts and related compounds (including all long-chain PFCA precursors). These groups cover many hundreds of related compounds. Organochlorinated pesticide is an umbrella term for a range of pesticides, including DDT and HCH.

Figure III

Sources of persistent organic pollutants

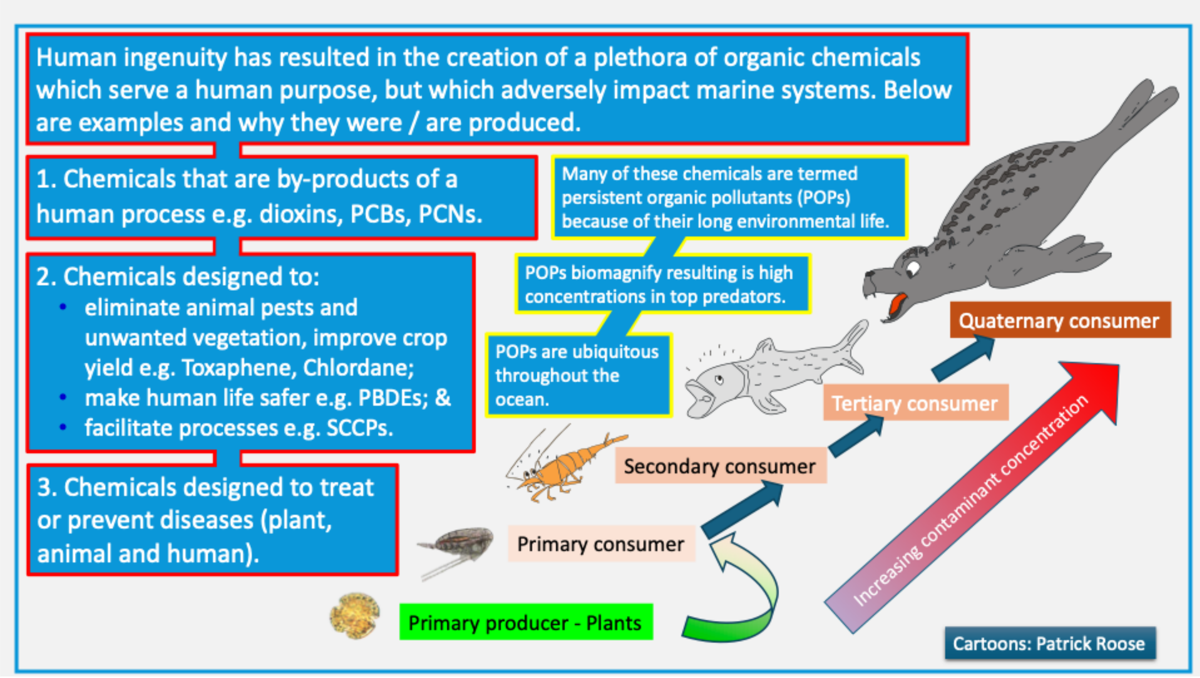


Source: Prepared by the writing team.

Note: Long-range atmospheric transport is primarily responsible for POPs found in the Arctic, Antarctic and other regions distant from the site of discharge. This means that POPs impact people and wildlife far from where they are released, which supports the finding in the second *World Ocean Assessment* that POPs continue to be global contaminants. Processes for removing POPs from wastewater continue to be investigated.

Figure IV

Persistence, bioaccumulation and biomagnification of persistent organic pollutants



Human ingenuity has resulted in the creation of a plethora of organic chemicals which serve a human purpose, but which adversely impact marine systems. Below are examples and why they were / are produced.

1. Chemicals that are by-products of a human process e.g. dioxins, PCBs, PCNs.

2. Chemicals designed to:
- eliminate animal pests and unwanted vegetation, improve crop yield e.g. Toxaphene, Chlordane;
- make human life safer e.g. PBDEs; &
- facilitate processes e.g. SCCPs.

3. Chemicals designed to treat or prevent diseases (plant, animal and human).

Many of these chemicals are termed persistent organic pollutants (POPs) because of their long environmental life.

POPs biomagnify resulting is high concentrations in top predators.

POPs are ubiquitous throughout the ocean.

Source: Cartoons by Patrick Roose.

Note: These processes mean that apex predators accumulate significant concentrations of POPs. Variation in concentrations can be associated with the prey consumed. Evidence published since the publication of the second *World Ocean Assessment* has shown that there are differences in the concentration of PCBs between killer whales (*Orcinus orca*) that had a mixed diet and those that had a diet mostly composed of fish. In addition, the concentration of PCBs in male killer whales was greater than in female killer whales regardless of diet (Remili and others, 2021). Cetaceans that forage on pelagic prey species had lower contaminant loads compared with those that were benthic or coastal feeders (Remili and others, 2024).

Concentrations of persistent organic pollutants in marine ecosystems

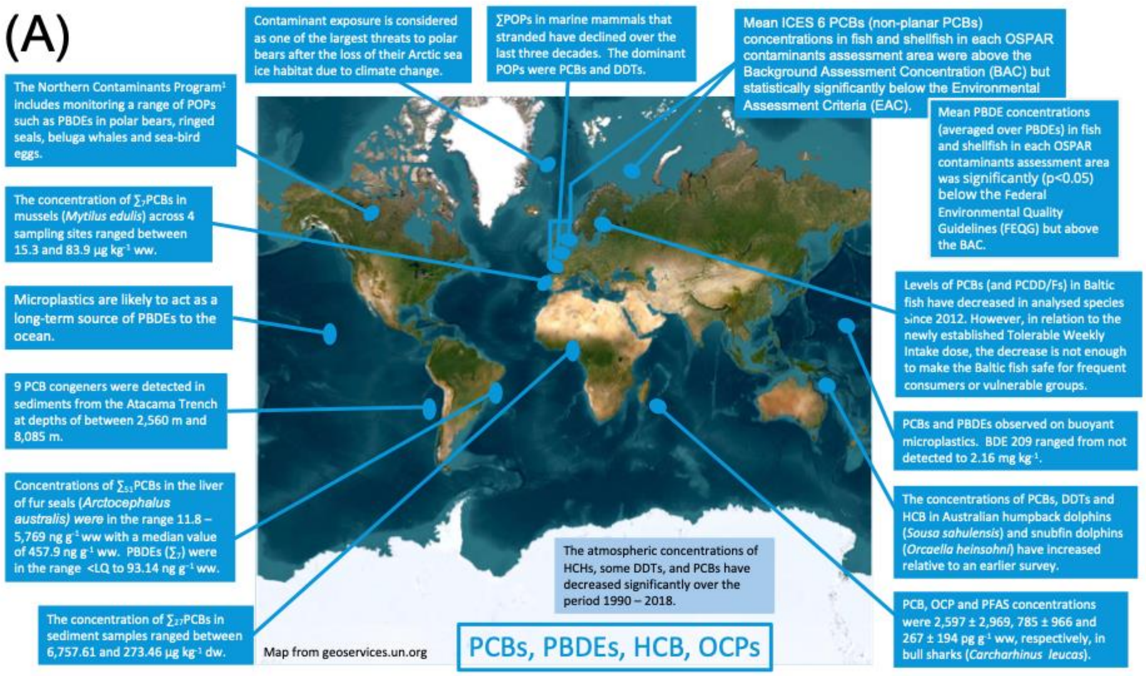
The present subchapter provides an update to the information on the concentrations of POPs in marine ecosystems contained in the second *World Ocean Assessment*.

Although the production and use of many POPs have been banned, POPs continue to be manufactured (see figure II). In the case of PCBs, for example, production has been banned for at least 30 years. In addition to legacy PCBs, there are “contemporary” PCBs that are inadvertently produced during the production of paints, dyes and other products (Hu and Hornbuckle, 2009) or during electricity production when coal is used as fuel (Montano and others, 2022; see figure II). Consequently, POPs are still present in all oceanic regions and continue to be transferred to the polar regions through atmospheric transport (see figures V.A to V.C). With these compounds being detected in marine ecosystems far from their source of production or emission (see box 1), the basis of regional assessments is the determination of the concentration of POPs in water, sediment or biota. These concentrations are then assessed relative to national or international assessment criteria. Wherever samples of water sediment or biota are collected, POPs are found. Concentrations of legacy POPs are very low in some cases, but PFOA and PFOS are found globally in seawater, sediments and plankton (see figure V.C). Time series are now long enough to enable temporal assessments for some POPs (Webster and Fryer, 2022). Replacement chemicals for listed POPs are also being detected in the ocean (Langberg and others, 2019).

Figure V

Concentrations of persistent organic pollutants in seawater, sediments and biota, in all regions

A. PCBs, PBDEs and HCB



The Northern Contaminants Program[1] includes monitoring a range of POPs such as PBDEs in polar bears, ringed seals, beluga whales and sea-bird eggs.

The concentration of $\sum_7$PCBs in mussels (*Mytilus edulis*) across 4 sampling sites ranged between 15.3 and 83.9 $\mu g\ kg^{-1}$ ww.

Microplastics are likely to act as a long-term source of PBDEs to the ocean.

9 PCB congeners were detected in sediments from the Atacama Trench at depths of between 2,560 m and 8,085 m.

Concentrations of $\sum_{51}$PCBs in the liver of fur seals (*Arctocephalus australis*) were in the range 11.8 – 5,769 $ng\ g^{-1}$ ww with a median value of 457.9 $ng\ g^{-1}$ ww. PBDEs ($\sum_7$) were in the range <LQ to 93.14 $ng\ g^{-1}$ ww.

The concentration of $\sum_{27}$PCBs in sediment samples ranged between 6,757.61 and 273.46 $\mu g\ kg^{-1}$ dw.

Contaminant exposure is considered as one of the largest threats to polar bears after the loss of their Arctic sea ice habitat due to climate change.

$\sum$POPs in marine mammals that stranded have declined over the last three decades. The dominant POPs were PCBs and DDTs.

Mean ICES 6 PCBs (non-planar PCBs) concentrations in fish and shellfish in each OSPAR contaminants assessment area were above the Background Assessment Concentration (BAC) but statistically significantly below the Environmental Assessment Criteria (EAC).

Mean PBDE concentrations (averaged over PBDEs) in fish and shellfish in each OSPAR contaminants assessment area was significantly ($p<0.05$) below the Federal Environmental Quality Guidelines (FEQG) but above the BAC.

Levels of PCBs (and PCDD/Fs) in Baltic fish have decreased in analysed species since 2012. However, in relation to the newly established Tolerable Weekly Intake dose, the decrease is not enough to make the Baltic fish safe for frequent consumers or vulnerable groups.

PCBs and PBDEs observed on buoyant microplastics. BDE 209 ranged from not detected to 2.16 $mg\ kg^{-1}$.

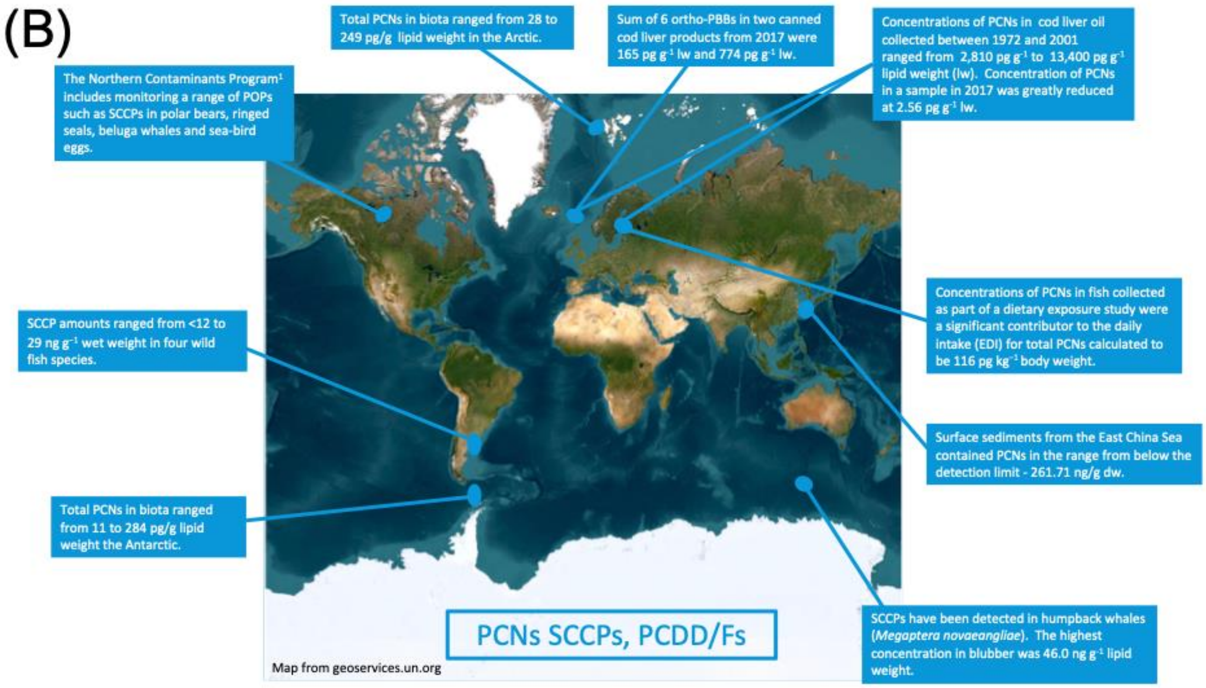
The concentrations of PCBs, DDTs and HCB in Australian humpback dolphins (*Sousa sahulensis*) and snubfin dolphins (*Orcaella heinsohni*) have increased relative to an earlier survey.

The atmospheric concentrations of HCHs, some DDTs, and PCBs have decreased significantly over the period 1990 – 2018.

PCB, OCP and PFAS concentrations were 2,597 ± 2,969, 785 ± 966 and 267 ± 194 $pg\ g^{-1}$ ww, respectively, in bull sharks (*Carcharhinus leucas*).

Map from geoservices.un.org

B. PCNs, SCCPs and PCDD/Fs



Total PCNs in biota ranged from 28 to 249 pg/g lipid weight in the Arctic.

Sum of 6 ortho-PBBs in two canned cod liver products from 2017 were 165 pg g^{-1} lw and 774 pg g^{-1} lw.

Concentrations of PCNs in cod liver oil collected between 1972 and 2001 ranged from 2,810 pg g^{-1} to 13,400 pg g^{-1} lipid weight (lw). Concentration of PCNs in a sample in 2017 was greatly reduced at 2.56 pg g^{-1} lw.

The Northern Contaminants Program[1] includes monitoring a range of POPs such as SCCPs in polar bears, ringed seals, beluga whales and sea-bird eggs.

Concentrations of PCNs in fish collected as part of a dietary exposure study were a significant contributor to the daily intake (EDI) for total PCNs calculated to be 116 pg kg^{-1} body weight.

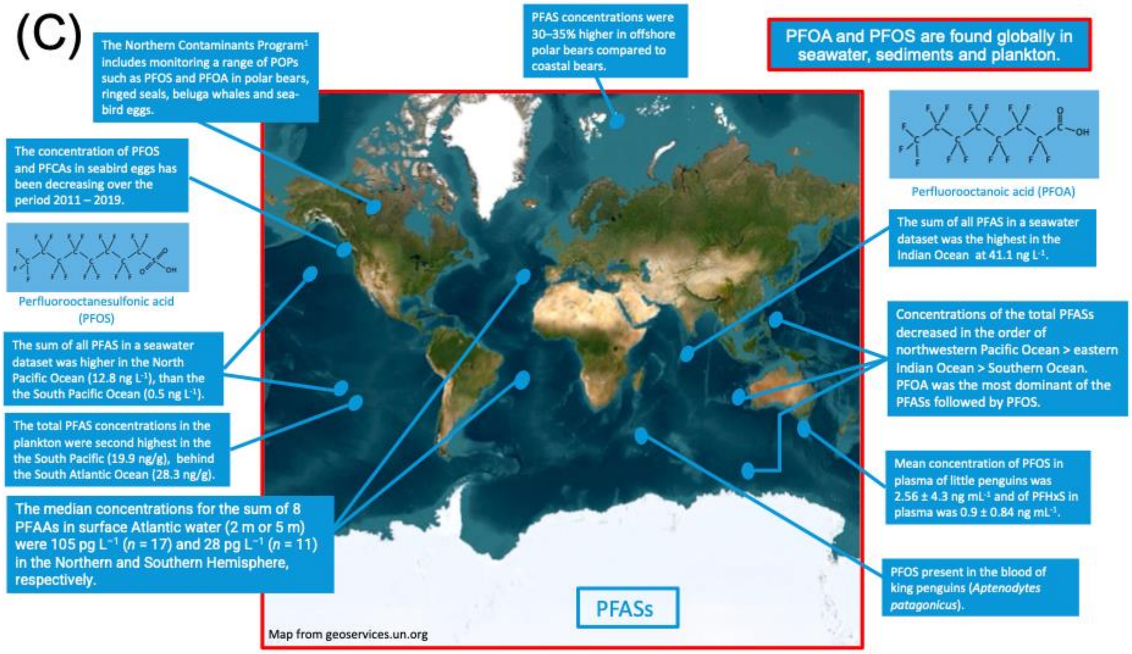
SCCP amounts ranged from <12 to 29 ng g^{-1} wet weight in four wild fish species.

Surface sediments from the East China Sea contained PCNs in the range from below the detection limit - 261.71 ng/g dw.

Total PCNs in biota ranged from 11 to 284 pg/g lipid weight the Antarctic.

SCCPs have been detected in humpback whales (*Megaptera novaeangliae*). The highest concentration in blubber was 46.0 ng g^{-1} lipid weight.

C. PFASs



PFOA and PFOS are found globally in seawater, sediments and plankton.

The Northern Contaminants Program[1] includes monitoring a range of POPs such as PFOS and PFOA in polar bears, ringed seals, beluga whales and sea-bird eggs.

PFAS concentrations were 30–35% higher in offshore polar bears compared to coastal bears.

The concentration of PFOS and PFCAs in seabird eggs has been decreasing over the period 2011 – 2019.

The sum of all PFAS in a seawater dataset was the highest in the Indian Ocean at 41.1 ng L^{-1}.

The sum of all PFAS in a seawater dataset was higher in the North Pacific Ocean (12.8 ng L^{-1}), than the the South Pacific Ocean (0.5 ng L^{-1}).

Concentrations of the total PFASs decreased in the order of northwestern Pacific Ocean > eastern Indian Ocean > Southern Ocean. PFOA was the most dominant of the PFASs followed by PFOS.

The total PFAS concentrations in the plankton were second highest in the the South Pacific (19.9 ng/g), behind the South Atlantic Ocean (28.3 ng/g).

Mean concentration of PFOS in plasma of little penguins was 2.56 ± 4.3 ng mL^{-1} and of PFHxS in plasma was 0.9 ± 0.84 ng mL^{-1}.

The median concentrations for the sum of 8 PFAAs in surface Atlantic water (2 m or 5 m) were 105 pg L^{-1} ($n = 17$) and 28 pg L^{-1} ($n = 11$) in the Northern and Southern Hemisphere, respectively.

PFOS present in the blood of king penguins (*Aptenodytes patagonicus*).

Sources: Prepared by the writing team based on Northern Contaminants Programme. Figure V.A: Chynel and others, 2021; Cagnazzi and others, 2020; Yeo and others, 2020; Mikolaczyk and others, 2021; Webster and Fryer, 2022; Williams and others, 2023; Routti and others, 2019; Esteves and others, 2024; Sobek and others, 2023; Turner, 2022; Pereira and others, 2024; Unyimadu and Benson, 2023; Luarte and others, 2023. Figure V.B Casa and others, 2019; Liu and others, 2018; Zacs and others, 2021; Falandysz and Fernandes, 2020; Falandysz and others, 2020; Dong and others, 2023; Girones and others, 2023; Dong and others, 2023. Figure V.C: Mollier and others, 2024; Wells and others, 2024; Shan and others, 2021; Khan and others, 2024; Muir and others, 2019; Kesic and others, 2023; Khan and others, 2024; Khan and others, 2024, Savvidou and others, 2023.

Box 2

Case study: Arctic Ocean region

Overview

Persistent organic pollutants (POPs) pose a significant environmental and health threat to the ocean due to their long-term persistence, potential for bioaccumulation and ability to travel long distances (Arctic Monitoring and Assessment Programme (AMAP), 2021). One of the most affected regions is the Arctic Ocean, which acts as a primary sink for POPs transported from industrial regions through atmospheric and oceanic pathways. The cold temperatures in the Arctic slow the degradation of these chemicals, allowing them to persist in the environment for extended periods.

Changes in the overall status

Since the second *World Ocean Assessment*, the concentrations of many legacy POPs, such as polychlorinated biphenyls (PCBs), dichlorodiphenyltrichloroethane (DDT) and hexachlorocyclohexanes (HCHs), have generally decreased in the Arctic region. Nevertheless, this positive trend is not without exceptions. Emerging contaminants, particularly perfluoroalkyl and polyfluoroalkyl substances (PFASs), have been increasingly detected in the Arctic. These substances, which were not previously recognized as significant threats, are now considered a growing concern due to their persistence, potential for long-range transport and bioaccumulative properties (United Nations Environment Programme (UNEP), 2019).

Factors contributing to the changes observed

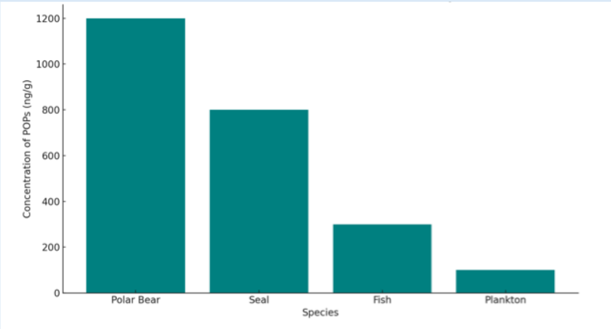
The decline of legacy POPs in the Arctic is primarily driven by international regulations, including the Stockholm Convention; regional initiatives, such as the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention) and AMAP; and a global shift in industrial practices. Reduced emissions and changes in atmospheric transport have lowered the influx of POPs to the Arctic, while environmental degradation processes and sequestration have further diminished their concentrations. As a result, POP levels have been significantly reduced, contributing to the protection of Arctic ecosystems and human health.

Impacts of the changes on, and interactions with, other components of the marine system

The changes in POP concentrations have significant implications for the Arctic marine ecosystem. POPs are known to be bioaccumulated in the Arctic food web, leading to high concentrations in apex predators, such as polar bears and seals, and there are detectable concentrations in fish and plankton (AMAP, 2020). This bioaccumulation disrupts the natural balance of the ecosystem, affecting the health and reproductive success of wildlife. Moreover, the re-mobilization of POPs due to climate change increases the risk of contamination in previously pristine areas, exacerbating the stress on already vulnerable species (Noyes and others, 2025). The figure below illustrates the bioaccumulation of POPs in different Arctic marine species, with a focus on apex predators. The data highlights particularly high concentrations of POPs in polar bears and seals, which pose significant health risks to these species and the ecosystems they inhabit.

Figure

Bioaccumulation of persistent organic pollutants in Arctic marine species



Source: AMAP (2021) and Johansen and others (2017).

Social, economic and cultural aspects associated with the change

The social, economic and cultural implications of POP contamination in the Arctic are profound, particularly for Indigenous communities, which rely heavily on marine resources for subsistence, cultural practices and economic activities. Contamination of key food sources, such as seals and fish, poses serious health risks, including increased cancer rates, endocrine disruption and reproductive issues (World Health Organization (WHO), 2018). Biodiversity loss and degradation of the marine environment threaten the cultural identity and traditional practices of Indigenous Peoples, who have coexisted with the Arctic environment for millenniums (Downie and Fenge, 2003). The economic impacts are significant, as the degradation of marine resources can affect the livelihoods of those who depend on fisheries and ecotourism. The long-term sustainability of such economic activities is at risk if POP contamination continues to undermine the health of the marine ecosystem.

Implications for achieving the targets for Sustainable Development Goal 14

The observed decline in POPs in the Arctic supports the achievement of several Sustainable Development Goals, particularly those related to environmental health, clean water and the protection of life below water and on land. Continued monitoring and policy enforcement are essential to maintain and further these gains, ensuring a safer and healthier environment for both human and ecological communities in the Arctic. Nevertheless, emerging contaminants (PFASs and hexachlorobenzene (HCB)) are becoming increasingly prevalent and might pose a major challenge to protecting the marine biodiversity of the Arctic. Climate change further complicates efforts to achieve the Goals because it alters the dynamics of POP distribution, transport pathways, sources and sinks, and increases the risk of contamination in previously unaffected areas (UNEP, 2019).

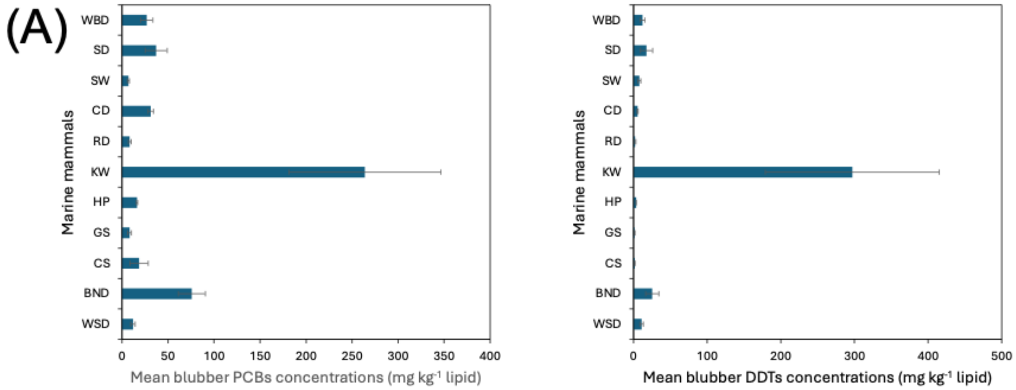
Achieving Sustainable Development Goal 14 requires a multifaceted approach, including strengthening international cooperation, enhancing regulatory frameworks and implementing targeted strategies to mitigate the impacts of POPs in the Arctic. The knowledge and perspectives of Indigenous communities must be integrated into such efforts to ensure that their cultural and socioeconomic needs are addressed in the pursuit of sustainable development.

Concentrations of POPs, including PCBs, DDT isomers, PBDEs, HCHs, HCB and dieldrin, in cetaceans are significant (see figures VI.A through VI.C; Williams and others, 2023). Data from cetacean strandings around Great Britain, however, show significant spatial and taxonomic heterogeneity and also reveal that the summed concentration of POPs, which was dominated by PCBs and DDTs, has declined for all species over the past 30 years. However, pollutants remain a threat to biodiversity in several species and regions covered in the study conducted by Williams and others (2023).

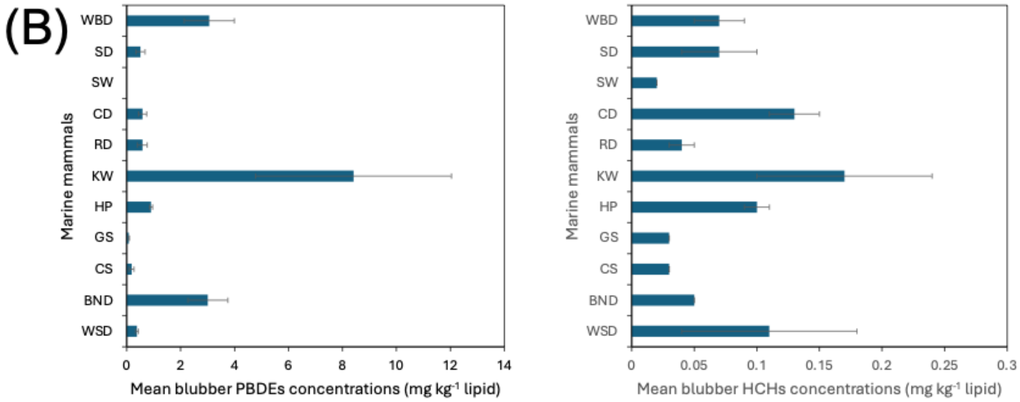
Figure VI

Mean concentration of persistent organic pollutants in the blubber of cetaceans

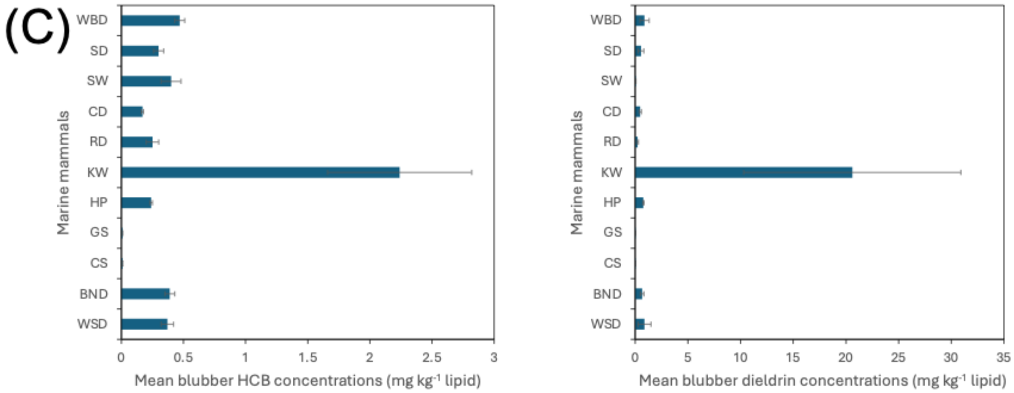
A. PCBs and DDT isomers



B. PBDEs and HCHs



C HCB and dieldrin



Source: Produced by the authors using data from Williams and others, 2023.

Note: Mean concentration in the blubber of 11 species of cetacean that had stranded on the coast of Great Britain over the period 1990–2018 with a decomposition code of less than four. The sample size for each individual species ranged from 6 (sperm whale) to 731 (harbour porpoise). Error bars reflect standard error.

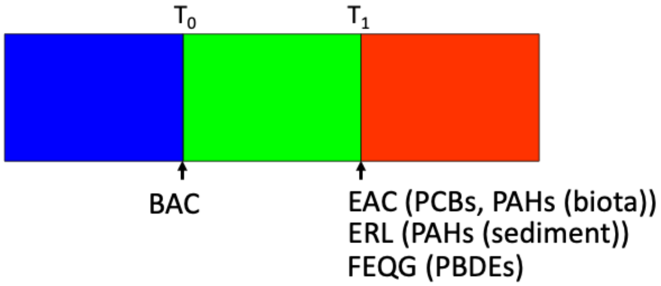
Abbreviations: BND, common bottlenose dolphin (*Tursiops truncatus*); CD, short-beaked common dolphin (*Delphinus delphis*); CS, common seal (*Phoca vitulina*); GS, the grey seal (*Halichoerus grypus*); HP, harbour porpoise (*Phocoena Phocoena*); KW, killer whale (*Orcinus orca*); RD, Risso’s dolphin (*Grampus griseus*); SD, striped dolphin (*Stenella coeruleoalba*); SW, sperm whale (*Physeter macrocephalus*); WBD, white-beaked dolphin (*Lagenorhynchus albirostris*); WSD, Atlantic white-sided dolphin (*Lagenorhynchus acutus*).

Use of assessment criteria

In recent years, assessment criteria have been increasingly used to determine the status of marine waters with respect to the concentration of hazardous substances, as exemplified by a recent assessment of hazardous substances in the North-East Atlantic (OSPAR, 2023). In that assessment, measured concentrations were classified into three categories: near natural background levels (for naturally occurring substances) or close to zero (for man-made substances); at or above the background assessment concentration but statistically significantly below the environmental assessment criteria or an alternative criterion selected for a given contaminant; or statistically significantly above environmental assessment criteria or the alternative (see figure VII). The results of the assessment give a clear indication of the status of marine biota, showing that although the concentrations of non-planar PCBs in fish and shellfish were all below the environmental assessment criteria in all areas assessed, concentrations of CB118 (a dioxin-like PCB) in biota were above the environmental assessment criteria in 7 of the 13 assessment areas, which indicates possible adverse effects on marine life in those areas (see figure VIII).

Figure VII

Range of assessment criteria used by the OSPAR Commission



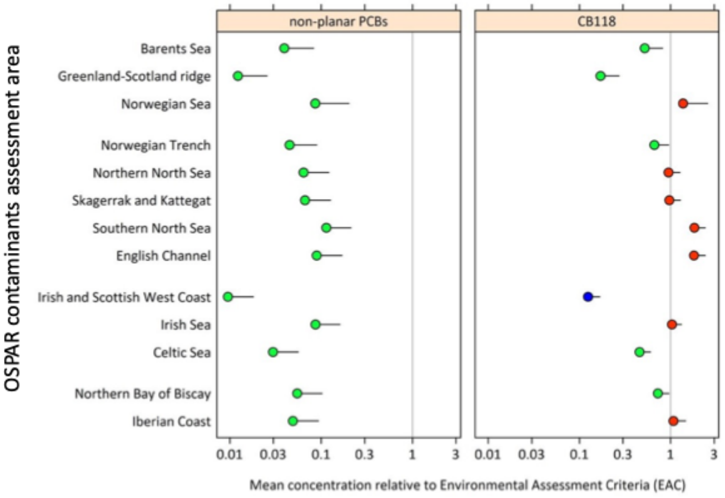
T: Transition point
BAC: Background Assessment Concentration (OSPAR / ICES. Testing whether measured concentrations are near natural background levels for naturally occurring substances and close to zero for man-made substances)
EAC, Environmental Assessment Criteria (OSPAR. Concentrations below EACs are considered to present no significant risk to the environment)
ERL, Effects Range – Low (US Environmental Protection Agency. Concentration of a chemical in sediment below which toxic effects are rarely observed among sensitive species)
FEQG, Federal Environmental Quality Guideline (Developed under the Canadian Environmental Protection Act from 1999. Concentrations below the FEQGs should not cause any chronic effects on marine organisms)

Source: Prepared by the writing team.

Note: A range of assessment criteria is used to assess the impacts of pollutants, including POPs. In this example, a blue status indicates that the concentration of the contaminant is statistically significantly below the background assessment concentration. The background assessment concentration is represented by the transition point T_0. T_1 represents the transition point between the concentration of a contaminant being at or above the background assessment concentration but statistically significantly below the environmental assessment criteria, on the one hand, and the concentration being statistically significantly above the environmental assessment criteria, on the other.

Figure VIII

Polychlorinated biphenyls in fish and shellfish, by OSPAR assessment area



Blue = statistically significantly below the BAC.
Green = at or above the BAC but statistically significantly below the EAC.
Red = statistically significantly above the EAC.

Source: OSPAR Commission, 2023; Webster and Fryer, 2022.

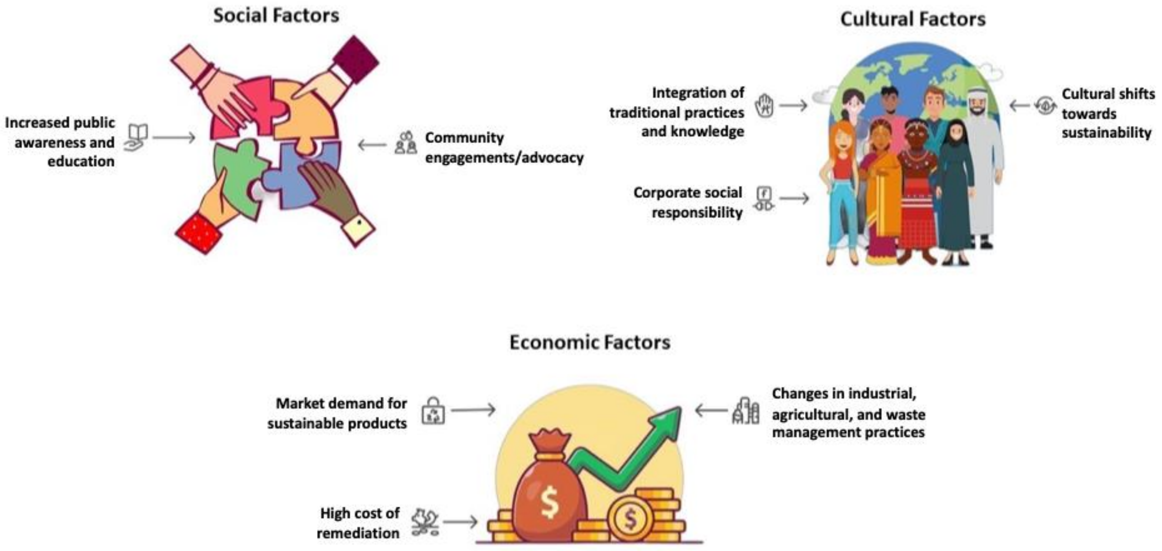
Note: This is based on the mean concentrations of PCBs (ICES-6 PCBs (non-planar PCBs) and CB118) in fish and shellfish in each OSPAR assessment area, relative to the environmental assessment criteria (with 95% upper confidence limits) where the environmental assessment criteria value is 1. Concentrations are statistically significantly below the environmental assessment criteria if the upper confidence limit is below 1. The concentrations of the non-planar PCBs were all below the environmental assessment criteria. Concentrations of CB118 in biota exceeded the environmental assessment criteria in 7 of the 13 assessment areas, which indicates possible adverse effects on marine life in those areas. The only area where the mean concentrations of CB118 in biota were below the background assessment concentration was the Irish and Scottish West Coast.

Drivers of the evolving societal response to persistent organic pollutants

The listing of POPs under the Stockholm Convention continues, which means that society is responding to the continuing problem of POPs and their impact on the environment. A combination of social, cultural and economic factors contribute to this societal response, and ultimately to a decline of concentrations of some POPs (see figure IX). For example, there is increased public awareness of the impacts of pollution on not only the ocean, but also on human health. There is also growing recognition that the ocean is vitally important as part of the living system of the Earth and central to building a healthy economy and a vibrant society. This recognition, together with the implementation of measures aimed at achieving the SDGs (as discussed below), has helped to engender a response from communities. Improved understanding by the scientific community and the wider public of the traditional practices and knowledge of Indigenous Peoples has also increased the awareness of environmental change due to human activities and raised the desire of people to reduce pollution. Lastly, changes in industrial, agricultural and waste management practices, owing in part to legislation but also to public demand for sustainable products, have helped.

Figure IX

Potential drivers of the decline in concentrations of some persistent organic pollutants



Source: Prepared by the writing team.

Note: Evidence points to an overall decline in the concentrations of at least some POPs. The potential reasons for that decline are multifactorial and include social, cultural and economic factors.

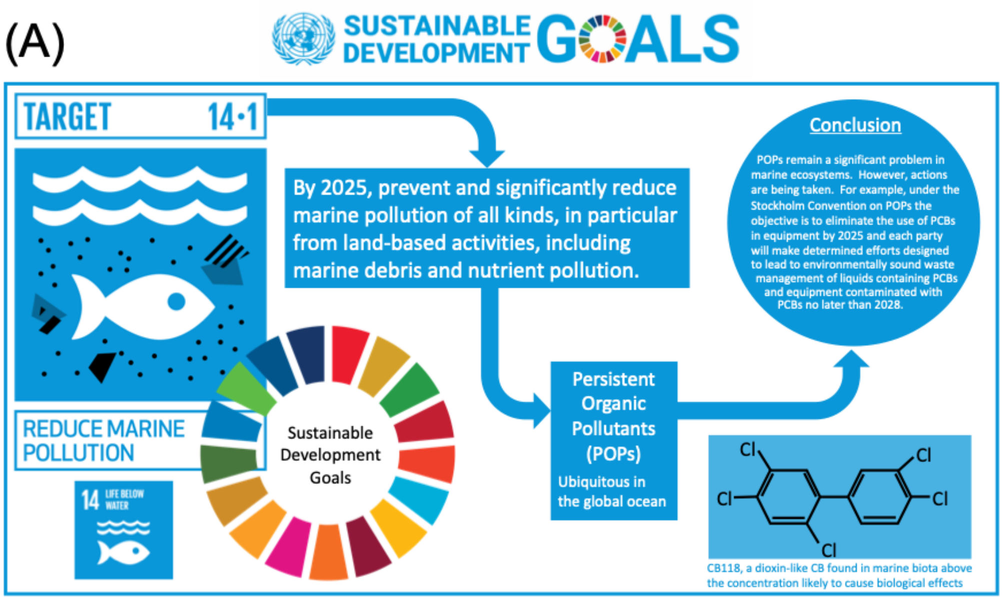
Ramifications for the Sustainable Development Goals

POPs are ubiquitous contaminants. Owing to the significant number of compounds and their varying half-lives, in 2025, the date set for Sustainable Development Goal target 14.1 (see figure X.A), concentrations of certain POPs will likely be shown, through ongoing monitoring programmes, to have been greater than the levels expected to cause biological effects. More important than the levels, however, is the impact on biota generated by the multitude of POPs to which the biota are exposed, which remains difficult to assess. POPs also continue to be of concern from a human health perspective, and thus have ramifications for target 3.9 (see figure X.B) and other Sustainable Development Goals target (see figures X.C through X.E).

Figure X

Ramifications for selected Sustainable Development Goal targets

A. Target 14.1, Reduce marine pollution



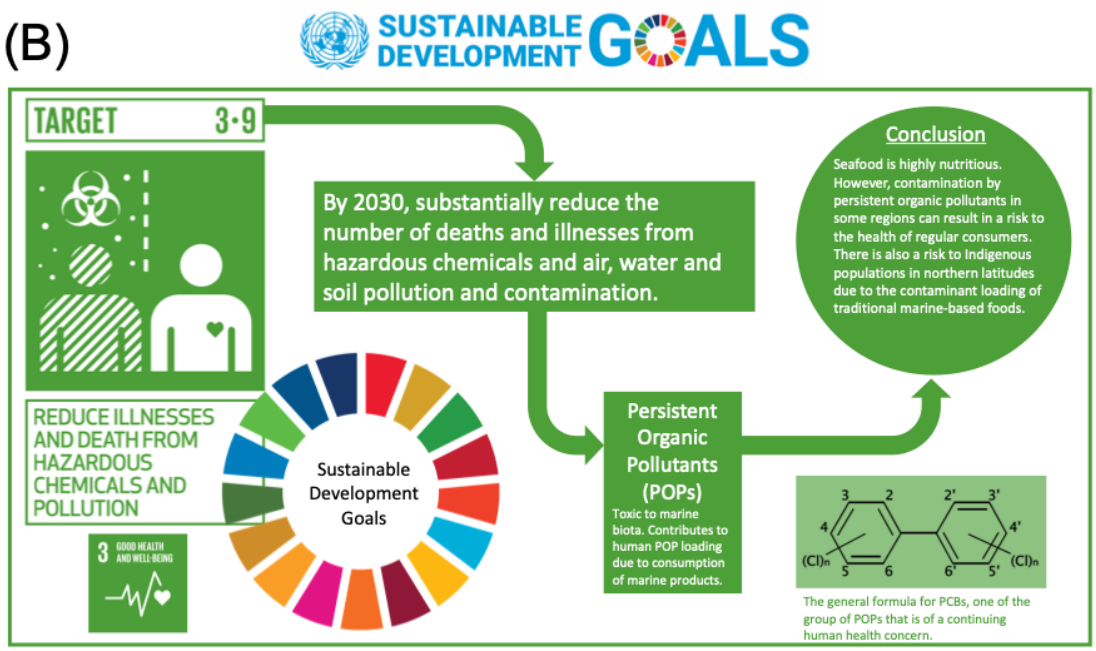
By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution.

Ubiquitous in the global ocean

POPs remain a significant problem in marine ecosystems. However, actions are being taken. For example, under the Stockholm Convention on POPs the objective is to eliminate the use of PCBs in equipment by 2025 and each party will make determined efforts designed to lead to environmentally sound waste management of liquids containing PCBs and equipment contaminated with PCBs no later than 2028.

CB118, a dioxin-like CB found in marine biota above the concentration likely to cause biological effects

B. Target 3.9, Reduce illnesses and death from hazardous chemicals and pollution



By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination.

Toxic to marine biota. Contributes to human POP loading due to consumption of marine products.

Seafood is highly nutritious. However, contamination by persistent organic pollutants in some regions can result in a risk to the health of regular consumers. There is also a risk to Indigenous populations in northern latitudes due to the contaminant loading of traditional marine-based foods.

The general formula for PCBs, one of the group of POPs that is of a continuing human health concern.

C. Target 6.3, Improve water quality, wastewater treatment and safe reuse

By 2030, improve water quality by reducing pollution, eliminating dumping, and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater, and substantially increasing recycling and safe reuse globally.

Reducing POPs in wastewater and preventing their release into water bodies is critical to achieving SDG 6. Strengthening wastewater treatment and preventing industrial pollution is key.

POPs, particularly the likes of PCDD/Fs and PCBs, can severely degrade water quality when they accumulate in waterways. These pollutants are often found in industrial wastewater and can contaminate water supplies.

D. Target 12.4, Responsible management of chemicals and waste

By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water, and soil in order to minimize their adverse impacts on human health and the environment.

Managing and reducing the production, use, and release of POPs is essential for achieving SDG 12, ensuring that these toxic chemicals are controlled to reduce environmental and human health impacts.

POPs are explicitly covered under the Stockholm Convention, an international framework for the management of hazardous chemicals and waste. SDG 12 aims to ensure that countries adopt practices that limit the production and disposal of hazardous substances like POPs.

E. Target 15.5, Protect biodiversity and natural habitats

By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water, and soil in order to minimize their adverse impacts on human health and the environment.

POPs are explicitly covered under the Stockholm Convention, an international framework for the management of hazardous chemicals and waste. SDG 12 aims to ensure that countries adopt practices that limit the production and disposal of hazardous substances like POPs.

Managing and reducing the production, use, and release of POPs is essential for achieving SDG 12, ensuring that these toxic chemicals are controlled to reduce environmental and human health impacts.

Source: Prepared by the writing team.

Ecotoxicology

When assessing the impacts of POPs on marine ecosystems, results are often presented by individual congener or by group of congeners. For example, an assessment might focus on a dioxin-like PCB, such as CB118, or on the ICES-6 PCBs (non-planar PCBs) (Webster and Fryer, 2022). Biota, however, are not exposed to one single congener or to one single group of congeners; they are exposed to all bioavailable pollutants in their geography. For this reason, ecotoxicological assessments are vital, because some ecotoxicological tests more correctly assess the impact of all anthropogenic chemicals in the environment rather than the impact of a single compound or group of compounds.

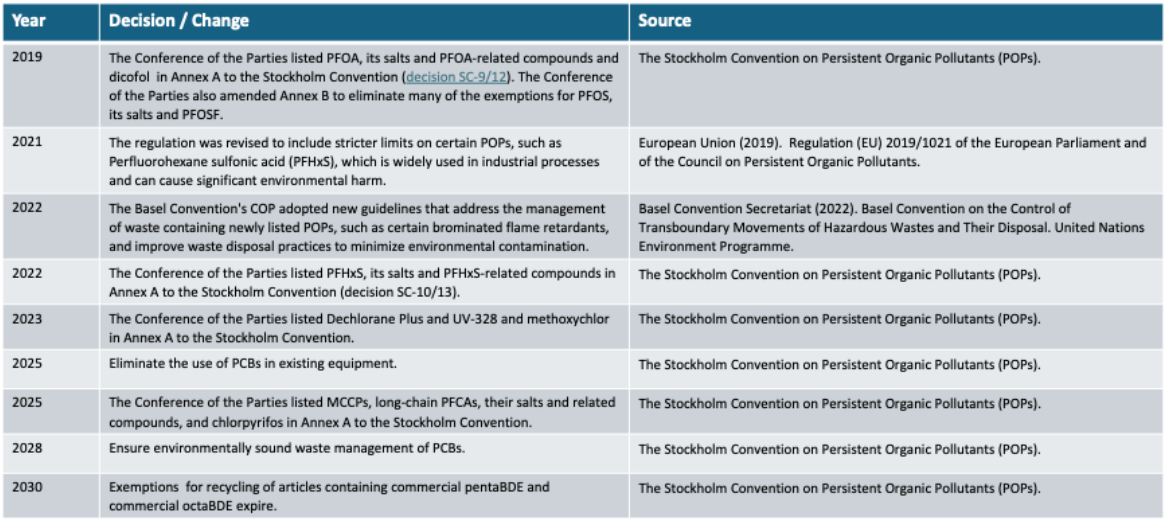
The understanding of the concentrations and impacts of POPs in the marine environment lags behind the understanding of their concentrations and impacts in freshwater systems because fewer marine-based ecotoxicity testing models and systems exist. Testing programmes, including the chemical monitoring programmes undertaken by such agencies as the Food Standards Agency of the United Kingdom, are focused on bioaccumulative compounds within high trophic species destined for human consumption. Data on other compounds, mixtures and congeners in the marine environment are therefore limited (Hutchinson, 2017; Tlili and Mouneyrac, 2021). Of increasing concern is the impact of mixtures of chemical compounds and the combined toxicity of environmentally realistic co-occurring contaminants with a dynamic exposure complexity, which is difficult to replicate in laboratory toxicity testing (Burgeot and others, 2023). Chemical contaminants can interact in multiple ways, and, according to one study, synergy occurs in 7% of binary pesticide mixtures (Cedergreen, 2014). Synergistic impacts are particularly concerning due to the potential for extreme impacts not predictable by single compound toxicity testing for regulatory purposes (Orr and others, 2024; Pirotta and others, 2022). To more accurately estimate the contribution of POPs to marine multi-stressor environments, combined toxicity estimations of mixtures are urgently needed, and profiles of how climate change is altering physical stressor conditions in the marine environment need to be taken into account.

Ongoing regulatory developments continue to bring change

As noted, the Stockholm Convention on Persistent Organic Pollutants serves as the basis for the global regulation of POPs. Table 2 contains a description of recent developments with respect to listed chemicals and selected targets for improving management of PCBs.

Table 2

Recent regulatory developments and selected targets



Year	Decision / Change	Source
2019	The Conference of the Parties listed PFOA, its salts and PFOA-related compounds and dicofol in Annex A to the Stockholm Convention (decision SC-9/12). The Conference of the Parties also amended Annex B to eliminate many of the exemptions for PFOS, its salts and PFOSF.	The Stockholm Convention on Persistent Organic Pollutants (POPs).
2021	The regulation was revised to include stricter limits on certain POPs, such as Perfluorohexane sulfonic acid (PFHxS), which is widely used in industrial processes and can cause significant environmental harm.	European Union (2019). Regulation (EU) 2019/1021 of the European Parliament and of the Council on Persistent Organic Pollutants.
2022	The Basel Convention's COP adopted new guidelines that address the management of waste containing newly listed POPs, such as certain brominated flame retardants, and improve waste disposal practices to minimize environmental contamination.	Basel Convention Secretariat (2022). Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal. United Nations Environment Programme.
2022	The Conference of the Parties listed PFHxS, its salts and PFHxS-related compounds in Annex A to the Stockholm Convention (decision SC-10/13).	The Stockholm Convention on Persistent Organic Pollutants (POPs).
2023	The Conference of the Parties listed Dechlorane Plus and UV-328 and methoxychlor in Annex A to the Stockholm Convention.	The Stockholm Convention on Persistent Organic Pollutants (POPs).
2025	Eliminate the use of PCBs in existing equipment.	The Stockholm Convention on Persistent Organic Pollutants (POPs).
2025	The Conference of the Parties listed MCCPs, long-chain PFCAs, their salts and related compounds, and chlorpyrifos in Annex A to the Stockholm Convention.	The Stockholm Convention on Persistent Organic Pollutants (POPs).
2028	Ensure environmentally sound waste management of PCBs.	The Stockholm Convention on Persistent Organic Pollutants (POPs).
2030	Exemptions for recycling of articles containing commercial pentaBDE and commercial octaBDE expire.	The Stockholm Convention on Persistent Organic Pollutants (POPs).

Abbreviations: COP, Conference of the Parties; MCCPs, medium-chain chlorinated paraffins.

Source: Prepared by the writing team.

Key remaining knowledge and capacity gaps and new gaps

Determining the impact of the chemical mixtures to which marine organisms are exposed continues to be a key challenge. This challenge is exacerbated by the impacts of other forms of pollution, including synergistic interactions with nanoplastics (Kamalakannan and others, 2024) and the impacts of changing temperatures, water oxygen concentration and acidity driven by increasing concentrations of greenhouse gases. Analytical challenges are significant because of the complexity of POP mixtures coupled with the analytical methods required for quantification of POPs in the ocean. Lastly, human ingenuity continues to result in emerging contaminants and POP replacements, including PHCZs (Gao and others, 2024). PHCZs have been detected in marine sediments, seawater, zooplankton, bivalves, fish, harbour seals and cormorant eggs (Wu and others, 2017; Hu and others, 2021; Hu and others, 2024). Recent studies have shown that 6:2 fluorotelomer sulfonate (6:2 FTS), which has been used as an alternative for legacy PFASs, may be immunotoxic (Grimberg and others, 2024; Bohannon and others, 2023). POP replacements are often not benign, which adds further complexity to the challenge of developing an understanding of the full impact and consequences of POPs in the ocean.

3. Pharmaceuticals and personal care products

Key points

- Advances in analytical techniques have significantly enhanced the identification and quantification of pharmaceuticals and personal care products (PPCPs) in marine environments, leading to more comprehensive data collection.
- Expanded monitoring programmes have led to a greater understanding of the prevalence of PPCPs in various oceanic regions, particularly in the North Pacific and North Atlantic.
- Studies have identified certain hot spots for the accumulation of PPCPs in coastal seas and have elucidated the effects of PPCPs on marine organisms, including such issues as bioaccumulation and toxicity to phytoplankton, fish and benthic species.
- Improvements to wastewater treatment technologies and adequate funding for the operation and maintenance of wastewater treatment facilities are necessary to reduce PPCP levels in effluents, thereby alleviating the pressure on coastal marine environments.
- Action plans and priorities have been developed on how to decrease the presence and potential impacts of pharmaceuticals in the environment. Strategies include reducing demand for and use of pharmaceuticals, improving disposal and reducing end-of-pipe emissions. The last and most expensive option is advanced wastewater treatment to remove active pharmaceutical ingredients (APIs) before their wider distribution in the environment (Caban and Stepnowski, 2021).

Introduction

PPCPs comprise a diverse array of substances, including prescription and therapeutic drugs, veterinary medications, fragrances, sunscreen agents and diagnostic compounds. At present, around 4,000 pharmaceutically active substances are available globally, and approximately 100,000 tons are consumed each year (Pawłowska and Biczak, 2024). PPCPs have increasingly generated significant environmental concern due to their persistence, bioaccumulative properties, toxic potential and, in many cases, high mobility (Chakraborty and others, 2023). Over the past few decades, many research and monitoring initiatives have employed advanced sampling and analytical techniques, such as liquid chromatography-mass spectroscopy, gas chromatography-mass spectrometry and non-targeted high-resolution mass spectrometry, to detect various PPCPs in the global ocean (Guo and others, 2023(b)). Commonly detected compounds include antibiotics, hormones and ultraviolet light (UV) filters, with concentrations of these substances varying across different regions.

The coronavirus disease (COVID-19) pandemic has further exacerbated this issue by significantly increasing the use of specific medications and treatments, notably antivirals, antimicrobials and antidepressants (Li and others, 2023). Mass consumption of some of these pharmaceuticals has led to a greater concentration of pharmaceutical residues in aquatic environments and river discharges. PPCPs are now pervasive in both the open ocean and coastal areas, with particularly high concentrations found near densely populated and industrial zones, wastewater discharge points, harbours and mariculture facilities (Lin and others, 2023). These pollutants can be transported through river outflows, ocean currents and atmospheric deposition, often accumulating in marine organisms and sediments, especially in marginal seas (Maghsodian and others, 2022).

The ecological impacts of PPCPs are profound and concerning. Toxicity studies have shown harmful effects on marine organisms, including endocrine disruption, the development of antibiotic resistance and behavioural changes in various marine biota, including fish, invertebrates and algae (Yang and others, 2020, Mezzelani and Regoli, 2022). The widespread presence of PPCPs poses a threat to marine biodiversity and ecosystem health. Moreover, human exposure to PPCPs, though less direct, remains a critical issue. This exposure primarily occurs through the consumption of seafood and participation in leisure activities in contaminated waters (National Academies of Science, Engineering and Medicine, 2024). Such exposure raises serious concerns about chronic health risks, including hormonal disruptions and the proliferation of antibiotic-resistant bacteria.

This assessment of PPCPs is focused on data and research published from 2018 to 2024. For information on PPCPs in the global ocean prior to 2018, see chapter 11 of the second *World Ocean Assessment*.

Environmental change since the second *World Ocean Assessment*

Recently, scientists have turned their attention to emerging chemical contaminants present in low concentrations, such as PPCPs, which pose significant threats to coastal and ocean environments through bioaccumulation and metabolism. Research and monitoring of the presence of PPCPs in marine waters is important, but there is a particular need to include metabolites in such efforts, as these compounds often go undetected and can be as persistent and hazardous as their parent substances. Table 3 shows the reported concentrations of PPCPs frequently detected in coastal waters around the world, including antibiotics, beta-blockers, antiulcer agents, antiepileptics, antiasthma drugs, antihistamines, calcium channel blockers, lipid-regulating agent and hormones .

Table 3

Pharmaceuticals and personal care products measured in coastal waters (ng/l)

Location	Antibiotics									
	Erythromycin		Clarithromycin		Roxithromycin		Sulfamethoxazole		Sulfamethazine	
	Before 2018	2018–2024	Before 2018	2018–2024	Before 2018	2018–2024	Before 2018	2018–2024	Before 2018	2018–2024
Baltic Sea	n.d.-0.14	n.a.	0.03–14	n.a.	n.d.-0.48	n.a.	0.74-21	n.a.	n.d.	n.a.
North Sea	0.13-0.94	n.a.	0.4-1.66	n.a.	n.d-2.86	n.a.	1.78-13.0	n.a.	n.d.	n.a.
Aegean Sea	n.d.	n.a.	16	n.a.	n.a.	n.a.	3.8	n.a.	n.a.	n.a.
Adriatic Sea	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.02 - 1.02	n.a.	n.a.	n.a.
Mediterranean Sea	9	n.d. - 2.3	5	n.d.-441.4	n.a.	n.d.-1.3	14	n.d.-99	n.a.	n.d.-9.1
Pearl River Delta (China)	n.d.-126	n.a.	n.a.	n.a.	n.d.-12.0	n.a.	n.d.-40.6	n.a.	n.a.	n.a.
Bohai Sea	n.a.	0-150	n.a.	0.82-37	n.a.	0-630	n.a.	0-140	n.a.	0-130
Yellow Sea	n.a.	0-121.2	n.a.	0-6.55	n.a.	0-11.8	n.a.	0-1.92	n.a.	0-250.66

East China Sea	n.a.	0-57.07	n.a.	0-6.38	n.a.	0.33-34.81	n.a.	0.81-16.65	n.a.	0-2.03
South China Sea	n.a.	0-1900	n.a.	0.06-1.5	n.a.	0-47	n.a.	0-17.5	n.a.	0-16.4
Boulder basin (United States)	<1.0	n.a.	n.a.	n.a.	n.a.	n.a.	5.4 ± 11	n.a.	n.a.	n.a.

Location	**ICM X-ray**				**NSAIDs**				**Antiepileptic**	
	Iomeprol		**Iopromide**		**Diclofenac**		**Ibuprofen**		**Carbamazepine**	
	Before 2018	2018–2024	Before 2018	2018–2024	Before 2018	2018–2024	Before 2018	2018–2024	Before 2018	2018–2024
Arctic, Longyearbyen (Norway)	n.a.	n.a.	n.a.	n.a.	1-4	n.a.	0.4-1	n.a.	n.a.	n.a.
Arctic, Tromsø (Norway)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.d. - 52	n.a.	n.a.	n.a.
Baltic Sea	1.05-34.5	n.a.	0.42-3.34	n.a.	n.d.-48	n.d.-27.1	n.a.	n.d.-1219.7	1.98-10.6	0.6-12.2
North Sea	7.66-207	n.a.	7.27-34.1	n.a.	n.d.-4.82	<MQL-35.35	n.a.	47.12-209.6	4.78-29.7	<MQL-78.9
Himmerfjärden (Sweden)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	4.0–12.0	n.a.
Aegean Sea	83	n.a.	109	n.a.	4.6	n.a.	n.a.	n.a.	2.9	n.a.
Adriatic Sea	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.11-0.36	n.a.
Sea of Marmara, Türkiye	n.a.	n.a.	n.a.	n.a.	n.a.	<MDL-1300	n.a.	<MDL-2130	n.a.	<MDL-1840
Mediterranean (Spain)	n.a.	n.a.	n.a.	n.a.	n.a.	n.d.-31.9	n.a.	n.a.	n.a.	n.d.-31.1
Mediterranean, (Tunisia)	n.a.	n.a.	n.a.	n.a.	n.a.	n.d.-23	n.a.	n.d.	n.a.	n.d.-0.5
Mediterranean (Italy)	n.a.	n.a.	n.a.	n.a.	n.a.	n.d.-441	n.a.	n.d.-2550	n.a.	n.d.-123
Gran Canaria	n.a.	n.a.	n.a.	n.a.	n.a.	n.d.-344	n.a.	n.a.	n.a.	n.a.
Tejo estuary (Portugal)	n.a.	n.a.	n.a.	n.a.	n.a.	1.6-51.8	n.a.	<LOQ	n.a.	n.d.
Bay of All Saints, Brazil	n.a.	n.a.	n.a.	n.a.	n.d.	n.a.	326.1-2094	n.a.	n.a.	n.a.
Guaruja (Brazil)	n.a.	n.a.	n.a.	n.a.	n.a.	85.7	n.a.	n.a.	n.a.	0.1

Sao Paulo coast (Brazil)	n.a.	n.a.	n.a.	n.a.	n.a.	9.9	n.a.	n.a.	n.a.	0.5
Santa Catarina (Brazil)	n.a.	n.a.	n.a.	n.a.	n.a.	7.9	n.a.	n.a.	n.a.	0.3
Red Sea	n.a.	n.a.	n.a.	n.a.	14020	n.d.-26.9	508	n.a.	110	n.a.
Klang River estuary (Malaysia)	n.a.	n.a.	n.a.	n.a.	n.a.	0.47-10.8	n.a.	n.a.	n.a.	n.a.
Durban (South Africa)	n.a.	n.a.	n.a.	n.a.	n.a.	n.d.	n.a.	170	n.a.	n.a.
Bohai and Yellow Sea	n.a.	n.a.	n.a.	n.a.	n.a.	<MDL-1.53	<MDL-5.11	<MDL-5.11	n.a.	n.d--38.26
Boulder Basin, (United States)	n.a.	n.a.	n.a.	n.a.	<1.0	n.a.	n.a.	n.a.	3.9±5	n.a.
Sydney estuary (Australia)	n.a.	n.a.	3-12.5	<0.1-94.3	n.a.	n.a.	n.a.	<0.5	n.d-2.7	<0.1-106.4

Location	**Lipid regulation (ng/L)**	**Beta-blockers (ng/L)**			**Antidepressants (ng/L)**	
	Bezafibrate	**Atenolol**	**Metoprolol**	**Propranolol**	**Fluoxetine**	**Citalopram**
Baltic Sea	n.d.-0.64	n.a.	0.1-0.8	n.a.	n.a.	n.a.
North Sea	n.d-2.06	<MQL-30.8	<MQL-23.5	<MQL-35.2	<MQL	<MQL-23.3
Aegean Sea	3.5	n.a.	n.a.	n.a.	n.a.	n.a.
Adriatic Sea	0.02-0.14	n.a.	n.a.	n.a.	n.a.	n.a.
Mediterranean (Spain)	n.d.-0.5	0.4-138.9	n.d.-5.1	n.d.-5.9	n.d.-0.6	n.a.
Mediterranean (Tunisia)	n.d.	n.d.	n.d.	n.d.	n.d.-41	n.a.
Mediterranean (Italy)	n.d.	0.1-451	n.a.	n.a.	n.a.	n.a.
Tejo estuary (Portugal)	0.84-13.4	0.49	n.a.	0.02-1.89	1.09-16.2	n.a.
Atlantic (Rías Baixas, Spain)	n.a.	n.a.	n.a.	n.a.	n.d.-10.6	n.d.-92.5
Guaruja (Brazil)	n.a.	0.3	n.a.	n.a.	n.a.	n.a.
Sao Paulo coast (Brazil)	n.a.	13.2	n.a.	n.a.	n.a.	n.a.
Santa Catarina (Brazil)	n.a.	3.2	n.a.	n.a.	n.a.	n.a.

Bohai and Yellow Seas	n.d.-3.55	n.d.-4.35	n.d.-0.46	n.d.-1.43	n.a.	n.a.
Puget Sound (United States)	n.a.	n.a.	1.5	n.a.	n.a.	n.a.
Sydney estuary (Australia)	n.a.	n.a.	<0.05-7.7	n.a.	<0.1-36	<0.1-2.6

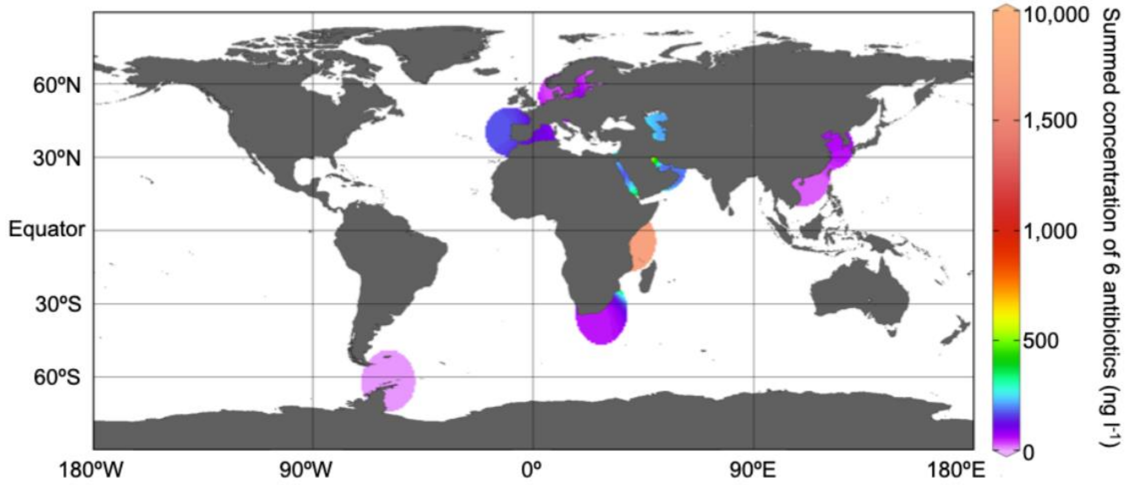
Abbreviations: ICM, iodinated contrast medium; LOQ, limit of quantification; MDL, method detection limit; MQL, method quantification limit; n.a., not available; n.d., not detected; ng/L, nanograms per litre; NSAIDs, non-steroidal anti-inflammatory drugs.

Source: Prepared by the writing team.

The variability of PPCP distribution is illustrated in figure XI, which shows the global distribution of six antibiotics in oceanic waters. High concentrations of antibiotics are concentrated near densely populated and industrialized coastal regions, particularly around Europe and East Asia. Moderate to high levels are also observed off southern Africa. In contrast, most open-ocean areas show low concentrations. Lower levels are evident in more remote regions, such as in the southern hemisphere and in polar areas.

Figure XI

Geographical distribution of selected antibiotics in the world's oceans



Source: Prepared by Zhiyong Xie, using Ocean Data View.

Note: The six antibiotics included are azithromycin, enrofloxacin, florfenicol, ofloxacin, sulfamethoxazole and trimethoprim.

A global monitoring study of pharmaceuticals in rivers, published in 2022, highlighted the potential transport of these compounds from river systems to the world's seas and oceans. The most contaminated samples reported were from rivers in Africa and Asia. As many as 53 APIs were detected at a single sampling site, and 4 APIs were detected in sampling sites on all continents: caffeine, nicotine, acetaminophen/paracetamol and cotinine (Wilkinson and others, 2022).

Region-specific changes

Arctic Ocean

PPCP residues have been detected in various environmental compartments, from coastal seawater to high-level biota, in the Arctic. The primary sources of these pollutants are local, domestic and municipal wastes, along with sewage. The lack of modern wastewater treatment plants in larger Arctic settlements results in higher PPCP release rates into the Arctic aquatic environment. By 2018, 110 PPCP-related substances had been found in the Arctic, with detectable residue concentrations. In the European Arctic, 11 pharmaceutical substances were measured in seawater and plankton samples collected in the Arctic fjord at Ny-Ålesund in 2019 (Korkmaz and others, 2022). 17-alpha-ethynylestradiol and fenoprofen were the most frequently detected pharmaceuticals, ranging from 340 to 850 nanograms per litre (ng/L) and 230 to 600 ng/L, respectively. These levels were higher than those of estrone (ranging from less than 43 to 420 ng/L) and 17-beta-estradiol (ranging from less than 29 to 140 ng/L), with the estrone detected likely being primarily a degradation product of 17-beta-estradiol. The diclofenac, ibuprofen and naproxen concentrations determined by Korkmaz and others (2022) were also higher than those found in other studies of the Arctic. Choi and others (2020) measured PPCPs in effluent and seawater collected at Ny-Ålesund using the target, suspect and non-target screening methods. PPCPs, including caffeine, paraxanthine, theophylline, acetaminophen, cetirizine, diethyl toluamide (DEET), and icaridin were detected in all samples, with concentrations ranging from 4 to 280,000 ng/L in effluents and from 2 to 98 ng/L in seawater. In the Canadian Arctic, organic diffusive gradients in thin film (o-DGT) passive samplers were deployed in Iqaluit and Cambridge Bay to monitor PPCPs in Nunavut (Stroski and others, 2020). Seven APIs (atenolol, carbamazepine, metoprolol, naproxen, sulfapyridine, sulfamethoxazole and trimethoprim) were found at least once, with concentrations varying from non-detectable to 5,200 ng/L. Due to the cold climate, these pharmaceuticals degrade slowly, resulting in prolonged presence. Consequently, the toxicological impact of PPCP release in the Arctic differs from that in temperate regions, posing exposure risks to local populations through contaminated fish and resistant microbes.

North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean Sea and North Sea

Adenaya and others (2024) analysed 62 APIs and one UV filter from the surface microlayer to the corresponding underlying water (0 cm, 20 cm, 50 cm, 100 cm and 150 cm) at four stations in the southern North Sea. Eleven APIs (caffeine, carbamazepine, gemfibrozil, ibuprofen, metoprolol, salicylic acid, clarithromycin, novobiocin, clindamycin, trimethoprim and tylosin) were detected in more than 95% of all seawater samples, while benzophenone-4, the UV filter, was detected in 83% .

Since 2020, following the recommendations from the Baltic Marine Environment Protection Commission (HELCOM), several studies have been carried out to investigate the occurrence, transport, sedimentation and bioaccumulation of APIs in riverine run-off and the estuaries of the Baltic Sea. In the eastern Gulf of Finland, seven APIs were identified in seawater samples, including caffeine (81%), carbamazepine (81%), ketoprofen (60%), diclofenac (23%), ciprofloxacin, trimethoprim, and clarithromycin, with concentrations varying from 0.1 to 4,500 ng/L. Antibiotics were found in trace amounts. In sediment samples, six APIs were detected with concentrations ranging from 0.1 to 66 ng/g (Chernova and others, 2021). Kucharski and others (2022) investigated 130 APIs in sediments collected from the Odra River estuary (south-west Baltic Sea). Of those 130 APIs, 48 were detected at concentrations above the limit of quantification in at least 10% of the sampling sites. Carbamazepine, sulpiride, fexofenadine, clindamycin, tramadol, bisoprolol and lidocaine were found to be the most frequently occurring compounds in the sediment. In most cases, levels of APIs recently measured in seawater and sediment from the Baltic Sea were in line with the levels detected in effluents from the surrounding region (Zandaryaa and Frank-Kamenetsky, 2021; Undeman and others, 2022; Jucyte-Cicine and others, 2024). Bobrowska-Korczak and others (2021) screened for 98 multi-class APIs, including cardiovascular drugs, antidepressants, antibiotics and sulfonamides, in the muscle tissue of fish caught in the Baltic Sea. Eleven pharmaceuticals (bisoprolol, carbamazepine, clarithromycin, erythromycin, fluoxetine, metronidazole, ofloxacin, promazine, sulfadimethoxine, thiabendazole and tianeptine) were detected in fish muscle, while none of them were found in bream and crucian, two of the seven species in the study.

The Danube River is an important source of PPCPs entering the Black Sea and the Mediterranean. Alygizakis and others (2016) measured PPCPs in seawater from the north-western part of the Black Sea using non-target screening and deep learning convolutional neural networks. Thirty-five PPCPs were tentatively identified by library spectrum match (Alygizakis and others, 2022). PPCPs have been measured in seawater from the Mediterranean since 2016 (Alygizakis and others, 2016). Of the 158 APIs targeted by Alygizakis and others, 38 were detected, 15 of which had frequencies of detection equal to or higher than 50%. Amoxicillin, caffeine and salicylic acid were the compounds with the highest detected values, with concentrations ranging from less than 5.0 to 130 ng/L, from 5.2 to 78 ng/L and from less than 0.4 to 53 ng/L, respectively. Western Mediterranean coastal areas, including Mar Menor lagoon in south-east Spain and the Ebro Delta in north-east Spain, have been screened for UV filters and synthetic musks. Musks (galaxolide (HHCB) and hexylcinamal) and UV filters (homosalate, ethylhexyl salicylate, octocrylene and dibutyl adipate) were detected in samples taken in those areas in summer months, with concentrations varying from a few ng/L to thousands of ng/L (García-Pimentel and others, 2023). In Augusta Bay, southern Italy, APIs were studied simultaneously in untreated wastewater (concentrations ranging from 2,426 to 67,155 ng/L), marine receiving water (concentrations ranging from approximately 550 to 27,889 ng/L) and seawater (concentrations ranging from approximately 12 to approximately 280 ng/L). These data demonstrate a clear concentration gradient, with API levels decreasing progressively from untreated wastewater to coastal receiving waters and further into offshore seawater (Feo and others, 2020). The substances with the highest concentrations in seawater included ciprofloxacin, ofloxacin, atenolol, irbesartan, losartan, valsartan and carbamazepine. Valsartan was detected at the highest concentration in all samples, ranging from 209 to 1,057 ng/L.

South Atlantic Ocean and wider Caribbean

PPCPs have been measured in seawater, sediment and biota in Camps Bay, off the South Atlantic coast of South Africa. Diclofenac, acetaminophen and carbamazepine present in sewage entered the Bay but were diluted quickly by the upwelling current(Ojemaye and others, 2022). The concentrations of caffeine, diclofenac and carbamazepine, all in the single ng/L range, were similar to levels detected in other marine regions, while concentrations of triclosan and acetaminophen were much lower than those found in other studies. UV filters were found in seawater and lionfish samples collected in Grenada, West Indies. Oxybenzone was the most frequently detected compound, with concentrations varying from not detected to 120 ng/L in seawater and from 0.12 to 2.9 micrograms per kilogram (mg/kg) wet weight in lionfish muscle (Horricks and others, 2019).

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

In the Indian Ocean, Ohoro and others (2021) studied APIs in water and sediment on the south-east coast of South Africa. Carbamazepine and trimethoprim were found in most sediment samples, with average concentrations of 8.75 ± 1.45 ng/g dry weight and 1.62 ± 0.83 ng/g dry weight, respectively. APIs were not detectable in seawater in all seasons. Ali and others (2017) found that concentrations of PPCPs in the Saudi Arabian coastal waters of the Red Sea were relatively high due to low water exchange with the open sea, ranging from 7 to greater than 3,000 ng/L for metformin, from less than the limit of quantification to 2,400 ng/L for acetaminophen and from 62 to more than 3,000 ng/L for caffeine. Daliri and others (2022) detected two antibiotics, amoxicillin and azithromycin, in urban wastewater discharged into the Persian Gulf, with concentrations of up to 335,000 ± 105,000 ng/L and 288,000 ± 38,000 ng/L, respectively, which shows that the volume of antibiotics being released into the northern Gulf is concerning. Mirzaie and others (2022) studied the concentration of azithromycin in seawater (7 ng/L) and sediment (5-10 ng/g) in the Persian Gulf in 2020 and found that levels were three to four times higher than pre-pandemic levels.

South and North Pacific Ocean

The coastal waters of the main island of Fiji in the South Pacific have been screened for pharmaceuticals. Seventy-two of 80 APIs were quantified at least once, with average concentrations ranging from 0.04 ng/L for diltiazem to 19 ng/L for ketoconazole (Dehm and others, 2021). Most studies carried out in the North Pacific have been focused on the marginal seas of China, the Republic of Korea and Japan. Near-shore areas exhibit higher PPCP levels due to direct discharge from urban wastewater and riverine inputs, with concentrations ranging from a few µg to a few ng per litre. Commonly detected PPCPs include antibiotics, antioxidants, analgesic and anti-inflammatory drugs, caffeine and synthetic musk fragrances. In contrast, offshore waters exhibit significantly lower concentrations, typically in the low ng per litre range, due to oceanic current dilution and degradation processes (Lu and others, 2023; Guo and others, 2023a). In the Bohai Sea (Guo and others, 2023b), PPCPs were widely detected in seawater, sediments and benthic organisms, with 1H-benzotriazole, an antioxidant, emerging as the most prevalent PPCP. Along the coasts of the Bohai and Yellow Seas, the total concentrations of 30 PPCPs in Chinese coastal waters ranged from 0.88 to 1200 ng/L, varying significantly from compound to compound but generally being higher than the concentrations of PPCPs in Korean coastal waters, which ranged from 9.9 to 440 ng/L.

Southern Ocean

Data on PPCPs in the Southern Ocean are scant due to its remoteness from the continents where PPCPs are used. Nevertheless, relatively high concentrations of PPCPs have been measured in glacial rivers and coastal seawaters near research stations. Concentrations of PPCPs in the Antarctic have been influenced mainly by the type of treatment systems used at research stations. The primary issue is the lack of tertiary treatment in most research stations, which leads to higher concentrations of PPCPs in their effluents. Wastewaters from Antarctic research stations have been found to contain 56 different PPCPs, while 23 PPCPs have been detected in nearby coastal waters and sea ice (Balakrishna and others, 2023). Concentrations of substances such as UV filters and antibiotics in wastewater are in the range of a few µg/L. In contrast, due to dilution and degradation, concentrations of the same substances in coastal waters and sea ice are two orders of magnitude lower (Emnet and others, 2015; Perfetti-Bolaño and others, 2022).

Remaining research gaps

Studies of PPCPs are predominantly focused on coastal areas that receive discharges from sewage, wastewater treatment plants and river run-off. Future research needs to be focused more on PPCPs in the open ocean and their long-range transport through ocean currents. There is also limited knowledge about the long-term ecological impacts of chronic high-level PPCP exposure on marine organisms.

Comprehensive data on global distribution of PPCPs are also lacking, especially in understudied regions, such as the South Atlantic, the Caribbean Sea, the South Pacific and the Indian Ocean. A lack of standardized methods for sampling, analysis and reporting further hinders efficient comparability for assessment and modelling.

Data on the full extent of PPCPs present in the global ocean are limited by non-validated methods and target analyte lists. Agreeing on a few PPCPs for baseline monitoring would help to fill in important data gaps.

Addressing these gaps is essential for effective mitigation of the impact of PPCPs on the global ocean, which includes expanded wastewater treatment, improved wastewater treatment technologies where treatment is already present, the provision of adequate funding for maintenance and operations, stricter regulations on the disposal and management of pharmaceuticals and enhanced public awareness about the environmental impact of PPCPs. The potential for long-term health effects necessitates further research and comprehensive risk assessments so that such risks can be better understood and mitigated. Continued research and international collaboration are essential to developing effective strategies to reduce the presence and impact of PPCPs, thereby protecting marine ecosystems and public health.

4. Plastic pollution

Key points

- Global plastic waste emissions are rising, with significant leakage from mismanaged waste, microplastic abrasion and loss, littering and marine activities.
- Plastics, especially microplastics, impact all marine ecosystems, with over 4,000 species affected. In some regions, there are debates on whether the impacts are significant.
- Plastic pollution costs billions of dollars annually. Addressing the issue requires reducing production, promoting reuse, rethinking product design, advancing material science innovations in recycling, controlling the full plastic life cycle and finding alternatives to single-use plastics in addition to legal bans to help to lessen the scale of the problem.
- Negotiations are currently under way to develop a legally binding treaty against plastic pollution, as called for in United Nations Environment Assembly resolution 5/14, to address the full life cycle of

plastic products and additives[1] in alignment with several Sustainable Development Goals and regional action plans from around the globe.

Introduction

Plastic pollution has been driven by the rise in production since the 1950s and the persistence of plastic in the environment (Geyer, 2020). Plastic waste emissions are estimated at 52.1 million metric tons per year; littering is the largest source in the global North, while uncollected waste is the largest source in the global South (Cottom and others, 2024).

Plastics, especially microplastics, impact all marine ecosystems (Suaria and others, 2020; Bergmann and others, 2022; Pierdomenico and others, 2023). Single-use plastics account for 40% of global litter, while fishing gear accounts for 15% (Morales-Caselles and others, 2021). Variations exist between high and low-income countries.

Changes since the publication of the second *World Ocean Assessment*

Changes in the overall status and contributing factors

Recently, there have been advancements in the understanding of marine plastic pollution owing to more precise data from satellite-based detection and other new methods for detecting microplastics and nanoplastics (Huang and others, 2023; Cózar and others, 2024). In addition, predictive tools have been developed (Rieger and others, 2024), and there are now regional assessments with common indicators agreed and monitored through regional seas conventions, including the OSPAR *Quality Status Report 2023*, the United Nations Environment Programme *Mediterranean Quality Status Report* and the HELCOM *State of the Baltic Sea 2023: Third HELCOM Holistic Assessment 2016–2021* . River and stormwater overflows driven by extreme weather events are major contributors of riverine litter (Lebreton and others, 2017; Meijer and others, 2021; Cózar and others, 2024; Nyberg and others, 2023; Zhang and others, 2023; Kaandorp and others, 2023).

Macro- and microplastics currently floating in the oceans and microplastics on beaches each account for 3 to 4% of total ocean plastic (Isobe and Iwasaki, 2022). Estimates indicate that there are 24.4 trillion pieces of microplastics in the world's upper oceans (Isobe and others, 2021). Plastics in deep-sea and coral reef ecosystems are also well-documented (Corinaldesi and others, 2021; Galgani and others, 2022; Nakajima and others, 2021; Pinheiro and others, 2023), and concentrations of plastics in remote areas and the deep sea are increasing (Galgani and others, 2021).

Studies have also shown that microplastics have infiltrated every ocean layer, including hadal trenches (Egger and others, 2020; Zhao and others, 2022, 2023 and 2025; Peng and others, 2018). Recent estimates indicate that there may be substantial microplastic concentrations in the water column, which are gradually exported to the deep ocean (Sonke and others, 2022; Harris and others, 2023).

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[1] The fifth session of the intergovernmental negotiating committee to develop an international legally binding instrument on plastic pollution, including in the marine environment, was held from 25 November to 1 December 2024 in the Republic of Korea.

Interactions with other components of the marine system

Plastic pollution poses a significant threat to marine habitats and natural processes, reducing ecosystem resilience, threatening human livelihoods and food security and causing harm to biota (see also subsect. 5A, subchaps. 1A, 1B and 1D on fisheries and aquaculture, chap. 4 on tourism and chap. 6 on shipping). According to the LITTERBASE online portal, 4,076 marine species are reportedly affected by litter.

Microplastics arise from multiple sources, including tyres, textiles, cosmetics, paint and the fragmentation of larger items (Weis and others, 2022; Thompson and others, 2024), with documented impacts to the environment (Tamis and others, 2021; Leistenschneider and others, 2023). While advanced sewage and wastewater treatment plants may remove some of these particles (Liu and others, 2021), millions still enter water bodies, and most contain toxic or hormonally disruptive additives, including phthalates and dyes.

Social, economic and cultural impacts

The social and economic costs of plastic pollution are significant, with the tourism, fishing and shipping sectors losing billions of dollars annually due to reduced revenue and cleanup activities (UNEP, 2021). While efforts to collect and recycle valuable plastics exist, solutions must prioritize innovation in material science, eco-design, reuse and durable alternatives to single-use plastics and fishing gear configurations, with recycling as the final option in the waste hierarchy. There are ongoing challenges with bioplastics, which can release microplastics, oligomers and toxic chemicals with largely unknown health risks (Paul-Pont and others, 2023; Zimmerman and others, 2020). Improved waste management technologies, such as those that incorporate artificial intelligence and robotics, and public engagement in sustainable practices and recycling are essential steps forward (Fang and others, 2023).

Policy developments at the international and regional levels

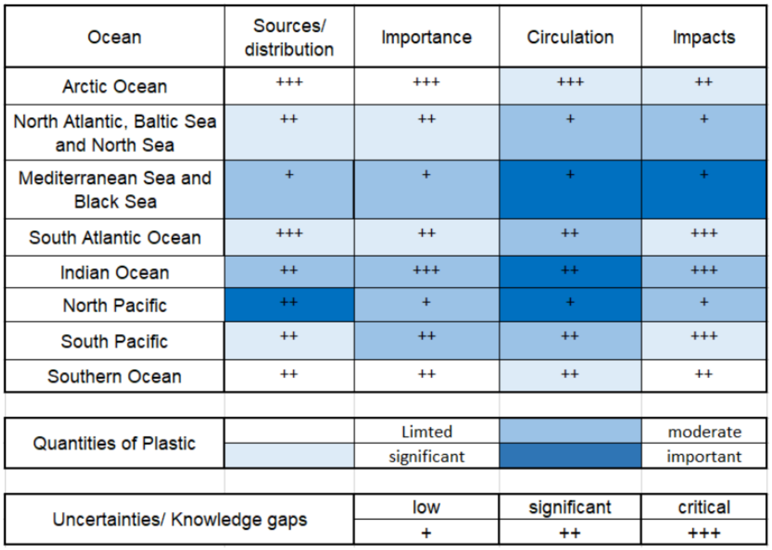
A number of global initiatives are being considered at various forums, including the negotiations on an international legally binding instrument on plastic pollution, including in the marine environment, as called for in United Nations Environment Assembly resolution 5/14. The negotiations represent a crucial step towards economic and social transformation (Center for International Environmental Law (CIEL), 2022; Lampitt and others, 2023; Maes and others, 2023; Syberg and others, 2024). In addition to containing essential provisions on downstream measures, such as advancements in waste management, the treaty ideally will apply a comprehensive approach to the plastic life cycle and emphasize prevention, in alignment with Sustainable Development Goals 3, 6, 11, 14 and 15 while complementing existing governance structures (Maes and others, 2023). The UNEP Regional Seas Programme also addresses ocean degradation, fostering collaboration among 143 member States through 18 regional seas conventions. Under 14 of those conventions, there are regional plans to combat marine litter, some of which are legally binding. These efforts are complemented by national and local action plans, as well as by active involvement of non-governmental organizations (NGOs).

Region-specific changes

The understanding of various aspects of plastic pollution, including the sources and the impact on the marine environment, vary across the different ocean basins (see table 4). Most recent scientific studies have found no significant change in the amounts of marine litter worldwide, with specific areas being classified as non-good status (UNEP, 2024), except in remote areas, where increasing amounts of plastic are found (Galgani and others, 2021). Nevertheless, there is evidence that certain components of plastic pollution have been decreasing in recent years, such as microplastics in the North Sea, thanks to the implementation of management, reduction and prevention measures and good practices (Kuhn and others, 2023). In addition, bans on priority single-use plastics recently adopted in some regions have led to significant reductions in beach pollution, with decreases of up to 30% in areas such as Europe, including the Mediterranean, and the United States (Marine Strategy Framework Directive (MSFD) Technical Group on Marine Litter, 2024; UNEP, 2024; Papp and Oremus, 2025).

Table 4:

Overview of the state of knowledge of marine litter in the different basins of the world ocean



Ocean	Sources/ distribution	Importance	Circulation	Impacts
Arctic Ocean	□ +++	□ +++	░ +++	░ ++
North Atlantic, Baltic Sea and North Sea	░ ++	░ ++	▒ +	▒ +
Mediterranean Sea and Black Sea	▒ +	▒ +	▓ +	▓ +
South Atlantic Ocean	░ +++	░ ++	▒ ++	░ +++
Indian Ocean	▒ ++	▒ +++	▓ ++	▒ +++
North Pacific	▓ ++	▒ +	▓ +	▒ +
South Pacific	░ ++	▒ ++	▒ ++	░ +++
Southern Ocean	□ ++	□ ++	░ ++	□ ++

Quantities of Plastic	□	Limted	▒	moderate
	░	significant	▓	important

Uncertainties/ Knowledge gaps	low	significant	critical
	+	++	+++

Source: Prepared by the writing team.

Note: The Caribbean Sea is included under the heading “South Atlantic”.

Knowledge and capacity gaps

UNEP, the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP), the Group of Seven (G7) and the Group of 20 (G20) support a comprehensive approach to assessing plastic pollution and its socioeconomic impacts, focused on monitoring, modelling and remote sensing (UNEP, 2021; GESAMP, 2019, 2021 and 2024; Ministry Of Environment, Forest and Climate Change of India (MoEFCC), 2023). Such an approach includes developing global mass balance models (Borrelle and others, 2020; Harris and others, 2023), conducting advanced life cycle impact analyses (Casagrande and others, 2024) that also take into account the economic and ecological costs of emissions and releases into environmental compartments, and exploring blockchain technology (Gong and others, 2022). The key components of the comprehensive assessment approach include standardizing methodologies, improving plastic flow tracking and defining source-to-sea indicators, as well as assessing the impact of marine litter on wildlife and socioeconomic systems. Innovative approaches like monitoring the biota found on plastic, ingested microplastics, water-column micro- and nano-plastics (Moon and others, 2024) and seafloor imagery are also crucial (Sandra and others, 2023). GESAMP (2021) has highlighted the gaps in data on sea-based sources of marine litter and dumped plastics.

6. Radioisotopes

Key points

- Assessments in the North-East Atlantic have found that discharges from nuclear power stations have continued to decrease since 2015. Comparable statistics are not compiled for other regions.
- Growing demand for non-carbon electricity has increased reliance on nuclear power, which is likely to lead to higher radioactive discharges.

Introduction

Radioisotopes in the ocean arise from both natural processes and anthropogenic inputs. Naturally occurring radioisotopes were examined in the first *World Ocean Assessment*, which continues to be the most recent global assessment available.

Developments since the publication of the second *World Ocean Assessment*, by source of anthropogenic input

Six main sources have led to anthropogenic inputs of radioisotopes to the ocean. An update since the publication of the second World Ocean Assessment is provided for each source.

Inputs from nuclear weapons testing

This source of inputs of radioactivity remains purely historical. However, the impact of nuclear weapons testing on the physical and mental health of Pacific Islanders remains evident (Patel, 2024; Pineda and others, 2023).

Inputs from nuclear incidents

There have been no significant nuclear incidents since the March 2011 incident at the Tokyo Electric Power Company’s Fukushima Daiichi Nuclear Power Station. Efforts to deal with the contaminated water in the station were based on three principles:

- Removing contamination sources
- Redirecting groundwater away from contamination source
- Preventing leakage of contaminated water

Measures to prevent leakage of contaminated water included the installation of a sea-side impermeable wall and a groundwater drainage system. This was installed to stop groundwater, which was ultimately pumped out, from flowing into the port area. These measures have led to the protection of the marine environment against pollution.

Japan has been analysing all water prior to its discharge into the sea to ensure that all radionuclides, other than tritium, are removed using an advanced liquid processing system (ALPS) and other systems to bring concentrations below regulatory standards. ALPS-treated water is discharged into the sea after being sufficiently diluted with seawater and after it has been confirmed that the concentration of tritium is below the regulatory standards. In the *IAEA Comprehensive Report on the Safety Review of the ALPS-treated Water at the Fukushima Daiichi Nuclear Power Station*, published in July 2023, the International Atomic Energy Agency (IAEA) concluded that the discharge of ALPS-treated water into the sea was consistent with relevant international safety standards and that the discharge would have a negligible radiological impact on people and the environment (IAEA, 2023a).[2]

Inputs from nuclear power plants

At the end of 2023, there were 413 nuclear power stations in operation worldwide, with a net electrical capacity of 373.7 GW (as compared with 450 stations with a capacity of 395 GW at the end of 2018) (IAEA, 2024). Assessments in the North-East Atlantic have found that discharges from nuclear power stations have continued to decrease since 2015 (OSPAR 2023, 2024). Comparable studies have not been conducted for other regions.

Discharges of tritium in cooling water are generally a significant component of radioisotope discharges from nuclear power stations, although they have relatively low radiological impact (Eyrolle and others, 2018). At present, industrial-scale abatement of tritium in cooling water discharges is not considered technically feasible (OSPAR, 2023).

A substantial increase in nuclear electricity generation is expected in the coming decades, in response to the need to reduce reliance on electricity from fossil fuels. The IAEA projects that worldwide nuclear electricity generating capacity is likely to increase from 371 GW in 2022 to between 458 and 890 GW in 2050 (IAEA, 2023b). Because tritium discharges from nuclear power plants are generally related to the level of activity, it is likely that this increase will be accompanied by increases in tritium discharges.

Inputs from nuclear fuel reprocessing plants

Where data are available, discharges from nuclear fuel reprocessing plants continue to be substantially more significant than discharges from nuclear power plants (OSPAR, 2023). Six of the

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[2] One country indicated that the report failed to fully reflect views from experts that participated in the review, and that the conclusion was not shared by all experts.

eight nuclear fuel reprocessing plants mentioned in the first and second *World Ocean Assessments* remain in operation. The plants in Tokai (Japan) and Sellafield (United Kingdom) have ceased operation (Japan Atomic Energy Agency (JAEA), 2023; Sellafield, 2022). A plant in Rokkasho, Japan, is expected to commence operations in 2026 (Japan Nuclear Fuel Limited (JNFL), 2024).

Inputs from industrial activities involving naturally occurring radioactive materials

There is no evidence of any significant global change since 2018.

Nuclear medicine

There is no evidence of any significant global change in the discharges from the clinical use of radiopharmaceuticals since 2018. However, the medicinal radionuclide and radiopharmaceutical market, as well as the theranostics market, are expected to grow. Furthermore, an increase in the use of outpatient procedures will mean an increased and uncontrolled excretion of radionuclides and their decay products into the environment (Pichler and others, 2025).

Changes in ocean due to the changing climate

It is highly likely that the impacts of climate change and ocean acidification will have many effects on the impacts of radionuclides on the ecology of the marine environment. Sea level rise, which exacerbates the impacts of cyclones and storm surges, will likely impact some nuclear power plants; to date, however, most have continued to operate during storm events (Gwynn and others, 2024).

7. Conclusion

Although some positive changes associated with the impact of regulation on emissions and discharges of all types have been documented, it is apparent that the ocean contains a complex array of chemicals and materials due to human activities on land and at sea. Despite decreasing concentrations of some legacy chemicals, those that remain are now joined by new, emerging contaminants, which means that the ocean contains an increasing number of chemical types.

The mobile nature of the ocean and atmosphere means that chemicals and materials can be found far from their sources. Every geographical location on the planet is therefore affected by chemical contaminants to some extent.

Ultimately marine biota continue to be affected by a vast array of chemicals, some carried on plastics and others that leach from plastics. Although the understanding of the impact of chemicals, including plastics, is improving, it remains extremely limited. There is, however, a growing body of evidence that pollution has many adverse impacts that combine with other pressures on exposed marine biota. The cumulative effects of multiple types of pollution and other external pressures are resulting in significant changes to marine ecosystems.

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