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SOS-ZEROPOL2030

D5.3 Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS) specific guidance to zero pollution in our seas

Public

Author(s): Thomais Vlachogianni, Rian Ruhl, Thomas Maes, Andy Booth, Lisa Devriese, Kathrin Kopke, Linda Del Savio, Judith Van Leeuwen, Emma Gileva, Aleksandar Shivarov, Wouter Jan Strietman

Research Institute(s): MIO-ECSDE, WR, GRIDA, SINTEF Ocean, VLIZ, UCC, RIFS, WU, BSNN

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Authors (alphabetical)	
Name	Organisation
Andy M. Booth	SINTEF Ocean
Linda Del Savio	Research Institute for Sustainability (RIFS) at GFZ
Lisa Devriese	Flanders Marine Institute (VLIZ)
Emma Gileva	Black Sea NGO Network (BSNN)
Kathrin Kopke	University College Cork (UCC)
Judith van Leeuwen	Wageningen University (WU)
Thomas Maes	GRID-Arendal (GRIDA)
Rian Ruhl	Wageningen Research (WR)
Aleksandar Shivarov	Black Sea NGO Network (BSNN)
Wouter Jan Strietman	Wageningen Research (WR)
Thomais Vlachogianni	Mediterranean Information Office for Environment, Culture and Sustainable Development (MIO-ECSDE)

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Executive Summary

Key messages

- Perfluoroalkyl and polyfluoroalkyl substances (PFAS) are a group of highly persistent synthetic chemicals that are widely detected across European marine environments.
- Their widespread presence is the result of extensive use in industrial processes and consumer products, combined with their ability to travel long distances through the environment.
- Both legacy and emerging PFAS compounds are relevant environmental pollutants.
- There is increasing concern about the substances formed when PFAS break down or change, and the toxic effects of exposure to mixtures of different PFAS.
- Existing EU policies address PFAS only partially, with notable gaps in coverage, monitoring, and enforcement of the full substance spectrum.
- Emission reduction at the source through substitution, phase-out of non-essential uses, and product redesign is the most effective long-term strategy for reducing PFAS pollution.
- Effective PFAS mitigation requires coordinated life-cycle action combining regulation, industrial innovation, advanced treatment technologies, and strengthened monitoring systems.

PFAS, often referred to as “forever chemicals”, comprise a large group of >12,000 human-made chemicals. Their widespread use in applications such as metal plating, fluoropolymer and semiconductor manufacturing, firefighting foams, and water-repellent consumer products (e.g., textiles) has led to extensive environmental emissions. Once released, PFAS can partition between water, sediments, and living organisms, with many being transported over long distances through air and water, even reaching remote regions far from where they were originally released. Their persistence in the environment stems from the extremely strong carbon–fluorine bonds, making them highly resistant to natural degradation processes. As a result, PFAS can remain in the environment for decades, accumulating over time through continuous releases and contributing to widespread contamination of terrestrial, freshwater and marine ecosystems, including European seas.

PFAS contamination is unevenly distributed, with the highest concentrations typically occurring in industrialised and densely populated regions. Although the production and use of compounds such as PFOS and PFOA have been restricted, they continue to be widely detected because of their persistence and ongoing release from contaminated soils, sediments, and other environmental reservoirs. At the same time, increasing numbers of emerging PFAS are being detected, despite limited toxicity data for many of these substances. Water is the primary transport pathway, carrying PFAS through rivers and waterways into coastal and marine environments, while some volatile PFAS-related chemicals can also undergo long-range atmospheric transport before deposition. Consequently, river mouths and coastal areas represent major entry points for PFAS into European seas.

PFAS are identified as priority pollutants within the Horizon Europe SOS-ZEROPOL2030 project because their persistence, mobility and widespread occurrence present major challenges to achieving the EU Zero Pollution ambition for marine environments. Monitoring data confirm that PFAS are ubiquitous across European seas, yet important uncertainties remain regarding environmental concentrations, transport pathways, toxicity of both parent compounds and transformation products, cumulative exposure, and long-term accumulation in sediments.

PFAS exposure in the environment typically occurs as complex mixtures rather than individual compounds. Organisms are simultaneously exposed to multiple PFAS, often alongside other environmental contaminants, and these mixtures may produce combined effects that differ from those of single substances alone. Such "cocktail effects" can be additive or, in some cases, synergistic, potentially leading to underestimation of risk when compounds are assessed individually. However, current regulatory frameworks are still largely based on single-substance evaluations and do not fully capture mixture toxicity or cumulative exposure. This represents an important scientific and regulatory uncertainty in understanding the overall risks associated with PFAS in the environment.

The EU has established a multi-layered policy framework to address PFAS pollution through the European Green Deal, the Chemicals Strategy for Sustainability, and the Zero Pollution Action Plan, supported by legislation including REACH, the POPs Regulation, the Water Framework Directive, the recast Drinking Water Directive, the revised Urban Wastewater Treatment Directive, the Environmental Quality Standards Directive, and the Marine Strategy Framework Directive. While these measures have strengthened PFAS management, regulatory coverage remains incomplete, particularly for short-chain (PFAS with shorter molecular structures) and novel PFAS. In addition, implementation, monitoring, and enforcement of these measures vary across Member States. Conventional wastewater treatment technologies are often unable to remove PFAS effectively, limiting the potential for end-of-pipe mitigation. Taken together, these limitations highlight prevention at source as the most effective long-term strategy for reducing PFAS emissions.

Addressing PFAS pollution therefore requires an integrated source-to-sea, life-cycle approach combining regulatory, technological, and societal measures. Source control aims to reduce PFAS production and use through substitution, product and process redesign, and development of PFAS-free alternatives. Process control focuses on minimising emissions during manufacturing and product use through improved industrial practices, containment, and closed-loop systems. End-of-pipe management addresses PFAS after release via advanced treatment technologies, remediation of contaminated sites, and safe management or destruction of PFAS-containing waste streams.

Effective implementation depends on robust monitoring, harmonised data collection and reporting, modelling tools, and information infrastructures that support evidence-based decision-making across the full life cycle of PFAS. It also requires coordinated action among policymakers, industry, researchers, water and wastewater utilities, and civil society, spanning product design, manufacturing, use, waste management, and environmental remediation. Although a range of treatment technologies is available or under development, uncertainties regarding PFAS behaviour, transformation products, removal efficiency, and scalability continue to limit their widespread application.

Alongside regulatory and technological measures, greater transparency throughout supply chains, improved public awareness, and stronger stakeholder engagement are essential for supporting decision-making and facilitating the transition towards PFAS-free alternatives. The successful implementation of mitigation strategies will also depend on a better understanding of their socio-economic implications, including technical feasibility, costs of implementation, cost-effectiveness, and the distribution of costs and benefits across stakeholder groups. Existing economic assessments suggest that the societal costs of inaction, including human health impacts, environmental remediation, and ecosystem service losses, may substantially exceed the investment costs required for mitigation. However, these cost–benefit relationships remain highly uncertain for many emerging pollutants, mitigation technologies, and policy options, highlighting an important area for future research and policy development.

1. Introduction

1.1. Purpose, Scope & Objectives

The Horizon Europe SOS-ZEROPOL2030 project aims to deliver a stakeholder-led European Seas zero-pollution framework to help achieve the European Union's long-term ambition of 'Zero Pollution' in European seas (https://soszeropol2030.eu). Central to the project is a source-to-sea approach (Box 1-1) to marine pollution, which recognises the complexity of pollutant sources, characteristics, effects, and pathways, and supports targeted actions across land, freshwater, and marine systems. In this context, perfluoroalkyl and polyfluoroalkyl substances (PFAS) are used as a case study pollutant for chemical pollution. PFAS refers to a class of >12,000 synthetic compounds characterized by carbon–fluorine bonds, which confer exceptional chemical stability, environmental persistence, and surfactant properties.

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

Source-to-sea refers to a comprehensive management strategy that takes a holistic view of the sources of, and solutions to, the problem of pollution. A source-to-sea approach is essential to address the intricate web of interconnected ecosystems comprising marine, land, and freshwater resources. Recognising the inherent interlinkages and dependencies among these ecosystems, the source-to-sea approach promotes coordinated actions that consider upstream and downstream linkages, ensuring that interventions in one part of the system do not inadvertently cause harm elsewhere (Granit et al., 2017; Mathews and Stretz, 2019; Del Savio et al., 2026). Implementing the source-to-sea approach involves several key components, including integrated governance across different sectors and administrative levels, robust data and monitoring across the source-to-sea continuum, aligned policies to ensure consistency and effectiveness of management, active community engagement for solutions that are context-specific and equitable, and adaptive management that can be adjusted based on monitoring data and changing environmental conditions (Granit et al., 2017; Mathews and Stretz, 2019; Del Savio et al., 2026).

This guidance translates the scientific and technical findings of SOS-ZEROPOL2030 into actionable recommendations for the prevention, reduction and mitigation of PFAS pollution in European seas. By providing clear, policy-relevant and practical guidance, this document aims to support policymakers and other stakeholders in implementing measures that reduce emissions at the source, mitigate environmental risks, and achieve measurable improvements in marine water quality.

The guidance sets out to:

- Synthesize knowledge on PFAS emissions, risks, governance and stakeholder insights gathered from the SOS-ZEROPOL2030 integrated assessments into practical guidance for action.
- Provide clear recommendations for policy and regulatory measures at European, national and local levels to reduce PFAS inputs to seas.
- Identify PFAS prevention, reduction and mitigation strategies and actions tailored to different sectors and stakeholders.
- Support informed decision-making, enabling policymakers and practitioners to prioritize interventions, allocate resources effectively, and monitor progress over a short term or medium-term horizon.
- Encourage coordination among relevant actors—including industry actors, research institutions, public authorities, and NGOs—to achieve comprehensive and sustained reductions in PFAS pollution.

1.2. Why PFAS Pollution Matters

PFAS are widely referred to as “forever chemicals” because of their exceptional resistance to environmental degradation processes, potential for bioaccumulation, and ability to travel long distances through both atmospheric and aquatic transport pathways (Ruhl et al., 2024; Maes et al., 2026). This persistence, combined with their extensive use in industrial applications such as metal plating, fluoropolymer and semiconductor manufacturing, as well as in firefighting foams and consumer products including water-repellent textiles, has led to their widespread and increasing presence in the global environment. To achieve the EU’s Zero Pollution Action Plan vision of reducing pollution to levels no longer harmful to health and ecosystems by 2050, alongside its 2030 targets for pesticides, nutrients, and microplastics and broader efforts to reduce exposure to hazardous chemicals, minimising PFAS releases is essential.

1.3. Target Audience

This guidance is intended for a wide range of stakeholders involved in reducing marine pollution from PFAS, including:

- **Policymakers** – at European, national, and local levels, including those working within European regional sea conventions level, responsible for developing, implementing, and enforcing regulations on PFAS production, use, emissions, and environmental quality standards across sectors such as chemicals, water, waste, and industrial emissions.
- **Industry actors** – including key PFAS-producing and PFAS-using sectors such as chemical manufacturing, fluoropolymer production, textiles and coatings, electronics and semiconductor industries, firefighting foam producers, and downstream users, who play a central role in substituting PFAS, redesigning products, and reducing emissions at source.
- **Researchers and academics** – providing scientific evidence on PFAS occurrence, fate and transport, toxicity, exposure pathways, and treatment technologies, supporting monitoring frameworks and evidence-based policy development.

- **Infrastructure and service providers** – including drinking water utilities, wastewater treatment operators, waste management facilities, and remediation service providers, responsible for monitoring, capturing, and mitigating PFAS releases and managing contaminated water, sludge, and waste streams.
- **NGOs and CSOs representatives** – supporting public awareness, environmental advocacy, stakeholder engagement, and knowledge translation on PFAS risks, regulation, and phase-out strategies, while promoting transparency and accountability.

1.4. Methodology

This guidance is based on a combination of scientific analysis, expert input, and stakeholder knowledge. It draws primarily on the findings of the SOS-ZEROPOL2030 integrated assessments, which examine emissions, environmental risks, and management approaches for PFAS pollution (Ruhl et al., 2024). In addition, it integrates evidence from the project's policy and governance analysis (Devriese et al., 2023; Van Leeuwen et al., 2023), Living Labs (Van Hulst et al., 2024a; Van Hulst et al., 2025; Kopke et al., 2026), SWOT analyses (Van Hulst et al., 2025), and stakeholder surveys (Vaupotič et al., 2024), collectively capturing diverse perspectives on the challenges, risks, and potential solutions related to PFAS pollution. The resulting synthesis is aligned with the SOS-ZEROPOL2030 Framework (Boteler et al., 2026) and Roadmap (Vlachogianni et al., 2026), which define the broader strategic lines of action for chemical contaminants to achieve zero pollution in European seas.

1.5. Typology of Measures for Tackling PFAS Pollution

Given their widespread use, environmental persistence, and difficulty of removal once released, PFAS pollution requires a comprehensive and integrated approach that combines regulatory and policy measures, technological solutions, and stakeholder engagement. To support structured decision-making, this guidance adopts a three-tiered typology of interventions based on where and how measures operate along the pathway from emission to environmental impact. This framework enables action across the entire life cycle of PFAS —from production and application to environmental release, transport, and end-of-life treatment— thereby supporting effective and sustainable pollution reduction strategies.

- **Source Control**: Measures that prevent or reduce the production and use of PFAS, including the substitution of PFAS with safer alternatives, redesign of industrial processes and consumer products, and the development of PFAS-free materials and technologies.
- **Process Control:** Measures that reduce PFAS emissions during manufacturing and use phases, such as improved industrial handling and containment, closed-loop production systems, and optimized operational practices to minimise releases.
- **End-of-Pipe Management:** Measures that capture, treat, or remove PFAS after release into the environment, including advanced water and wastewater treatment technologies, remediation of contaminated soils and sediments, and other approaches aimed at limiting environmental dispersion and exposure.

In addition, **enabling control measures** refers to cross-cutting tools and systems — such as monitoring, data collection, modelling, and information systems — that support, inform, and optimize interventions across source, process, and end-of-pipe control categories.

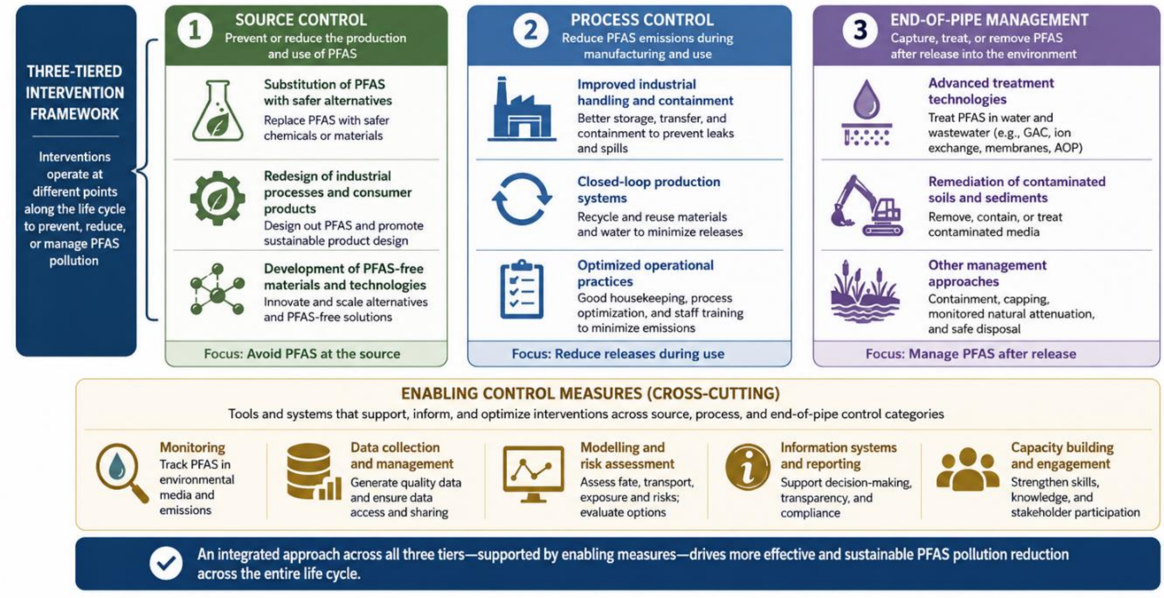

Figure 1-1. *A three-tiered typology of interventions for tackling PFAS.*

2. Understanding PFAS Pollution

2.1. What are PFAS?

The Organisation for Economic Co-operation and Development (OECD) defines PFAS as substances containing at least one fully fluorinated methyl (-CF3) or methylene (-CF2-) carbon atom, devoid of hydrogen, chlorine, bromine, or iodine substituents (Ahmed et al., 2020). PFAS are a large and structurally diverse group of human-made chemicals characterised by strong carbon–fluorine bonds, which give them unique properties such as exceptional resistance to heat, water, oil and chemicals (Buck et al., 2011; Sadia et al., 2023; Jamaluddin et al., 2026). As a result, many PFAS can only be broken down under extreme conditions, such as very high-temperature incineration (typically above 1000 °C for the most stable compounds) or exposure to UV radiation, such as that found in the upper atmosphere (Xin et al., 2023; Pocorobba & Braiman, 2025). Some PFAS contain weaker chemical linkages, such as ester or ether bonds, which can lead to partial degradation into smaller transformation products. However, these transformation products are often still classified as PFAS. As a result, environmental degradation does not necessarily eliminate PFAS, but can instead lead to the formation of other PFAS that may remain highly persistent and continue to spread in the environment (Ruhl et al., 2024).

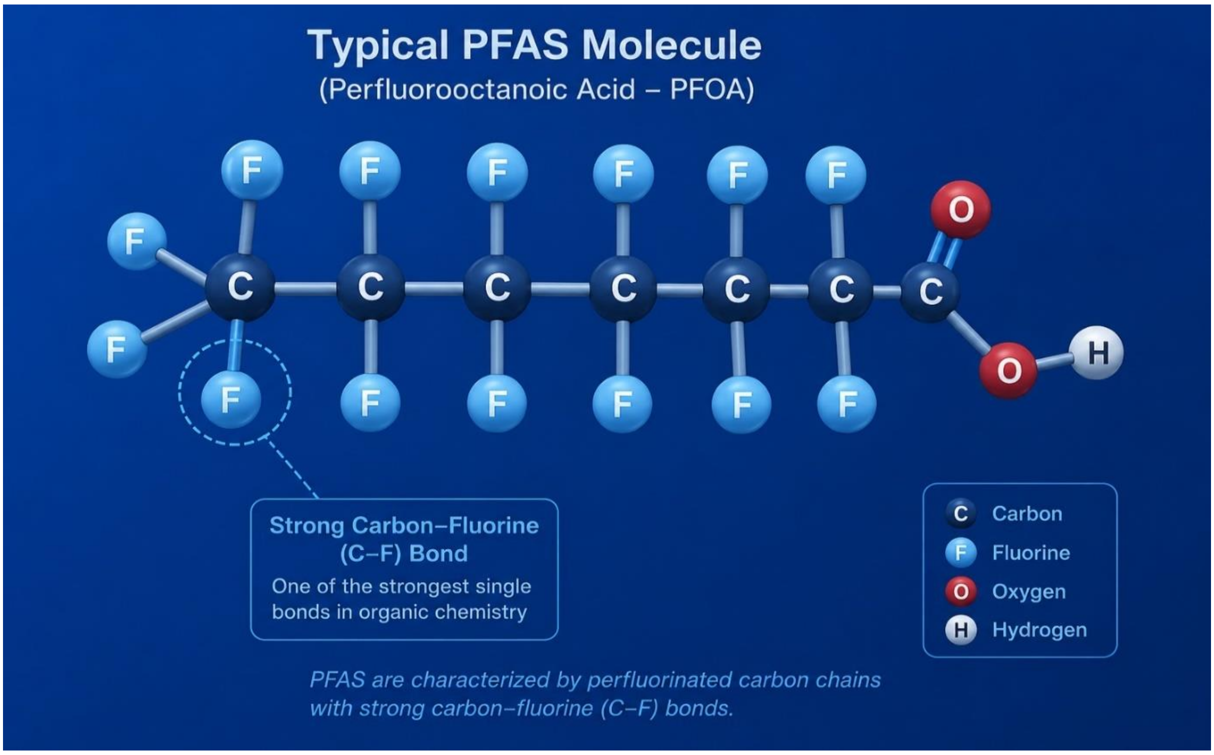

Figure 2-1. A typical PFAS molecule (PFOA).

These same properties that make PFAS attractive for specific technological and consumer product applications also means they are highly persistent in the environment and difficult to break down once released (Lenka et al., 2021; Cordner et al., 2021). Owing to this environmental persistence, concerns have emerged regarding the long-term impacts of PFAS on ecosystems and public health. The number of different PFAS detected in the environment is growing. The approximately 4,700 substances described by the OECD in 2017 grew to more than 12,000 documented by the US

Environmental Protection Agency (EPA) in 2023 (Schymanski et al., 2023). PFAS can be broadly classified into several groups based on their chemical structure, usage history, environmental transformation pathways or stages of regulatory and scientific attention (Buck et al., 2021; Liu et al., 2026), as follows:

- **Legacy PFAS:** consist of long-chain perfluoroalkyl carboxylic acids (PFCAs), such as perfluorooctanoic acid (PFOA) and perfluorononanoic acid (PFNA), and perfluoroalkyl sulfonates (PFSAs), such as perfluorooctanesulfonic acid (PFOS) and perfluorohexanesulfonic acid (PFHxS). These compounds are well known for their persistence, bioaccumulation potential, and historical widespread use. Many of these compounds are now restricted or subject to phase-out under EU chemicals legislation.

- **Short-chain replacement PFAS**: include shorter-chain perfluoroalkyl carboxylic acids (PFCAs) such as perfluorobutanoic acid (PFBA), perfluoropentanoic acid (PFPeA), and perfluorohexanoic acid (PFHxA), and perfluoroalkyl sulfonates (PFSAs) such as perfluorobutanesulfonic acid (PFBS). These were introduced as substitutes for legacy PFAS. Although they generally exhibit lower bioaccumulation potential (the tendency of a substance to accumulate in living organisms over time), they tend to be more mobile in aquatic environments and can therefore be transported more readily through rivers, groundwater, and other water systems.

- **Emerging replacement PFAS:** primarily consist of ether-based compounds such as fluoroether acids. These substitutes for legacy PFAS include compounds such as hexafluoropropylene oxide dimer acid (HFPO-DA, commonly known as GenX), ammonium 4,8-dioxa-3H-perfluorononanoate (ADONA), and F-53B (a proprietary perfluoroalkyl ether sulfonate mixture). Although these substances were introduced as alternatives to legacy PFAS, concerns remain regarding their environmental behaviour, particularly their high mobility, persistence, and the limited understanding of their potential impacts on human health and ecosystems.

- **PFAS precursors:** include fluorotelomers and phosphate esters such as 6:2 fluorotelomer sulfonate (6:2 FTS), 8:2 FTS, fluorotelomer alcohols (FTOHs), and polyfluoroalkyl phosphate esters (PAPs). Although these substances may be less persistent in their original form, they can transform in the environment into stable PFAS that are highly resistant to degradation, contributing to long-term contamination and exposure risks.

- **Ultra-short-chain PFAS and their degradation products:** are short-chain acids such as trifluoroacetic acid (TFA) and perfluoropropionic acid (PFPrA). These substances are highly mobile in aquatic environments and can spread readily through rivers, groundwater, and other water systems, and are often difficult to remove using conventional water treatment technologies.

- **Novel or unknown PFAS:** include suspect or non-target PFAS such as unidentified perfluoroether carboxylic acids (PFECAs) and proprietary surfactants. This group highlights the ongoing challenge of fully characterizing the expanding diversity of PFAS in the environment.

2.2. Sources, Pathways and Fate of PFAS

PFAS pollution originates from both point sources and diffuse sources. Point sources are emissions from specific, identifiable locations such as industrial facilities, whereas diffuse sources arise from widespread activities across society, including the use and disposal of PFAS-containing consumer products. In Europe, the largest point-source emissions originate from PFAS production facilities, with estimated releases of approximately 750 tonnes per annum (A&O Shearman, 2026). Production sites have also been estimated to release 27–57 tonnes to surface waters in 2020 (Ruhl et al., 2024).

However, it remains highly uncertain how much and which PFAS are released from waste management processes, including wastewater treatment plants (WWTPs), incinerators, and landfills, with emissions potentially occurring to air, surface water, and groundwater. Of particular concern is that PFAS incineration may not achieve complete destruction under suboptimal operating conditions, potentially resulting in residual emissions or by-products.

Flemish companies were required to self-monitor PFAS emissions into surface waters from industrial activities, including manufacturing, downstream uses, and waste treatment. Using these Flemish monitoring data as a basis for extrapolation, total European point-source emissions to surface waters have been estimated at approximately 26 tonnes per annum (Ruhl et al., 2024). This suggests that self-reporting systems can provide useful insights into point-source emissions, but may still significantly underestimate total release volumes, even under mandatory monitoring schemes.

Diffuse PFAS emissions account for the vast majority of total emissions. They occur mainly during the use phase and broadly follow usage volumes of PFAS-containing substances and products across sectors (Fig. 2-2). PFAS in solid applications are generally associated with lower emission volumes during the use phase.

While the original PFAS Restriction Report and its Annexes identified the textiles, upholstery, leather, apparel, and carpets (TULAC) sector as the largest source of diffuse emissions, the Background Document to the Opinion on the Annex XV dossier proposing restriction (ECHA, 2025) indicates that the transport sector is associated with the largest volume of diffuse PFAS emissions, with the TULAC sector ranking second.

Based on the information compiled in the EU PFAS restriction proposal it can be concluded that (Ruhl et al., 2024):

- A small number of application groups (gases, textiles/TULAC, medical devices, construction, manufacturing) are accountable for the largest share of diffuse PFAS emissions in the EEA.
- Diffuse PFAS emissions are likely to be higher in total volume than emissions from point sources. As measurements cannot be performed for all sources of diffuse PFAS emissions, it is challenging to trace a specific chemical in the environment back to the original products or use cases.
- Some PFAS chemical manufacturing sites are currently important point sources for emissions into air and wastewater. They may also be the origin of a large share of PFAS emissions from chemical waste incinerators related to PFAS manufacturing.
- The use of certain PFAS, such as PFOS and PFOA, has been restricted in the EU since 2009 and 2020, respectively. However, in 2022 they still accounted for a significant share of

PFAS detected in Flemish wastewater. This may be related to the slow release of legacy PFAS from firefighting foams and other long-lived applications, the continued import of products containing these substances into the EU, and the environmental transformation of precursor PFAS into PFOS and PFOA.

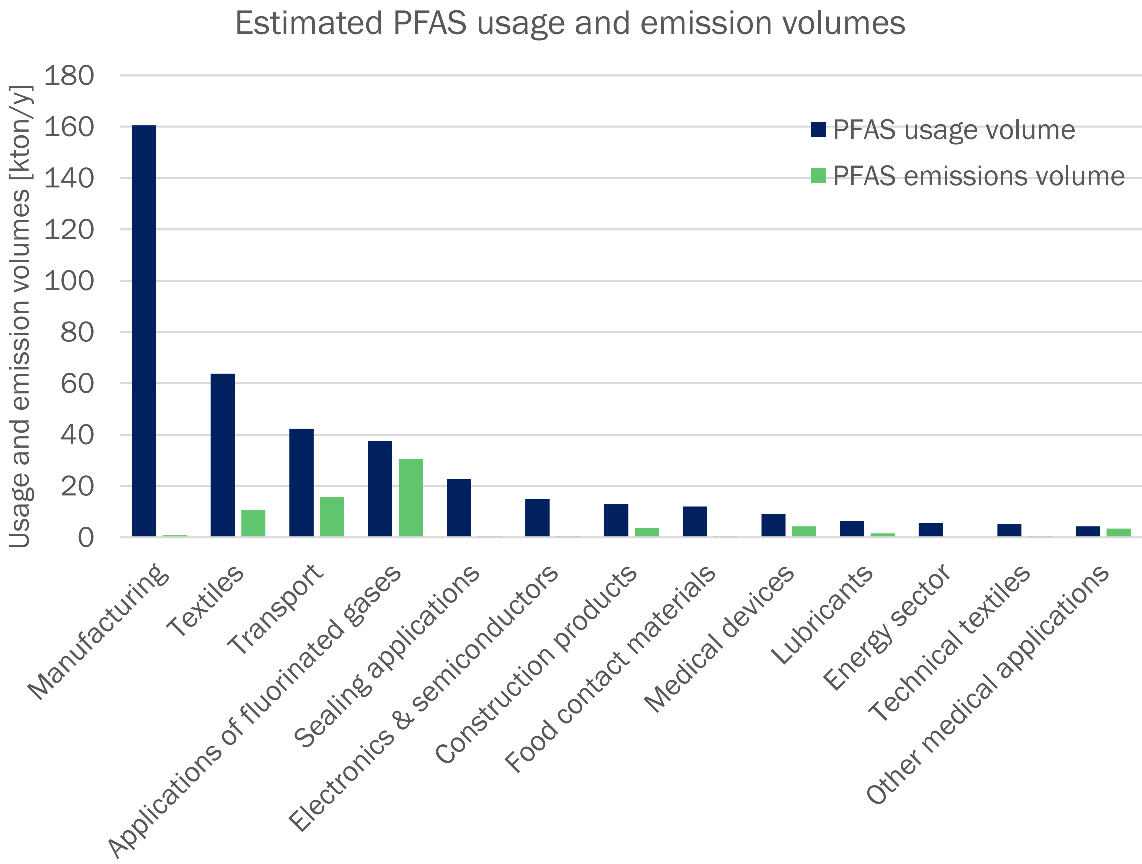

Figure 2-2. *Usage and emission volumes for PFAS in the European Economic Area, based on estimations in the restriction proposal for PFAS under REACH, with data relating to the year 2020 (ECHA, 2023).*

Current evidence suggests that transport through water is the primary pathway for PFAS in the environment. Some PFAS precursors can also undergo long-range atmospheric transport before transforming into persistent PFAS (Dunn et al., 2024). Although much of the existing research has focused on PFAS transport from contaminated sites such as airports, military installations, and firefighting training areas, PFAS have also been detected in remote regions, demonstrating their capacity for long-range environmental transport (Rankin et al., 2016; Li et al., 2023). In aquatic environments, PFAS distribution is further influenced by horizontal and vertical transport processes, and they may also adsorb onto suspended particles, sediments, and microplastics, particularly for more hydrophobic (typically long-chain) PFAS compounds (Li et al., 2023).

As a result, the marine environment represents a major terminal sink for PFAS, as many ultimately reach rivers and coastal waters before entering the sea (Muir & Miaz, 2021). PFAS concentrations in seawater are therefore often highest in coastal regions, particularly near estuaries and river mouths where large amounts of PFAS are discharged into the sea (Joerss et al., 2019; Ahrens et al., 2023).

2.3. Environmental and Human Health Impacts

PFAS are known to disrupt endocrine function, impair developmental processes, and reduce reproductive capacity in aquatic organisms (Barmentlo et al., 2015; Samal, 2026). They also adversely affect the growth and survival of fish, amphibians, and invertebrates, ultimately altering food web structure and reducing biodiversity (Bhattacharya et al., 2024; Thapa et al., 2024). Through bioaccumulation and biomagnification, PFAS concentrations increase progressively at higher trophic levels, leading to elevated exposure in top predators (Merino et al., 2018; Tahir et al., 2023; Li et al., 2021). Beyond these well-documented ecological effects, PFAS exposure has been associated with a broad range of adverse biological outcomes in marine and other organisms, including oxidative stress, neurotoxicity, immune dysfunction, and metabolic disturbances such as hyperglycemia and lipid accumulation, as well as hormonal imbalance and alterations of the gut microbiome (Hong et al., 2025).

Human exposure to PFAS depends on the nature of contact and ingestion pathways, which include contaminated drinking water, contaminated food such as fish and agricultural products, inhalation of contaminated dust, and occupational exposure in PFAS-related industries (Samal, 2026). Dietary intake is considered a major exposure route for the general population. The European Food Safety Authority (EFSA) reported that seafood accounts for the largest share of dietary PFAS exposure, contributing approximately 86% of total intake, while meat, dairy products, and agricultural crops also make significant contributions (Knutsen et al., 2018).

Studies in human populations have consistently linked PFAS exposure to disruptions in endocrine function and metabolic regulation, including changes in thyroid hormone levels, blood lipid levels, and blood sugar regulation (Kim et al., 2018; Gui et al., 2023). Associations have also been reported between PFAS exposure and reproductive outcomes, such as reduced fertility, decreased birth weight, and developmental effects in infants and children (Johnson et al., 2014; Gui et al., 2022). In addition, PFAS exposure has been linked to immune system suppression, including reduced vaccine antibody response, as well as increased susceptibility to infections (Grandjean et al., 2012). Further evidence suggests potential associations with liver damage, including signs of impaired liver function, such as elevated liver enzyme levels, and the accumulation of excess fat in the liver, as well as possible links to certain cancers, particularly kidney and testicular cancer, although causality and mechanistic understanding remain under active investigation (Gallo et al., 2012; Barry et al., 2013).

The health impacts of PFAS exposure have been documented in the Beveren–Kruibeke–Zwijndrecht (BKZ) region of Flanders, where historical emissions from industrial activities have resulted in elevated environmental and human exposure levels (Peters et al., 2022). A VITO (Flemish Institute for Technological Research)-led biomonitoring study involving 303 adolescents aged 12–17 years living within 5 km of the 3M facility reported significantly higher PFOS concentrations in blood compared with adolescents from the general Flemish population (Consortium UAntwerpen et al., 2023). The study identified associations between higher PFAS exposure and changes in immune function, hormonal regulation, growth, and pubertal development, consistent with findings from the wider scientific literature. Notably, only around one-quarter of participants had PFOS blood concentrations below internationally recognised health-based guidance values. The results suggest increased vulnerability of young people to long-term PFAS exposure and underscore the importance of continued source reduction, exposure prevention measures, and long-term health monitoring in affected communities.

3. Assessing the Problem

3.1. Key Findings from the SOS-ZEROPOL2030 PFAS Risk Assessment

As part of the EU SOS-ZEROPOL2030 project, a scenario-based risk assessment framework was developed for complex pollutants and emerging contaminants, such as PFAS (Ruhl et al., 2024; Maes et al., 2026). The PFAS risk assessment process integrated a detailed exposure assessment based on reported exposure concentrations and modelled data across different European regional seas with a hazard assessment based on database and literature toxicity data and modelling. Within this risk assessment, PFAS chemicals were divided into legacy PFAS (PFOS and PFOA) and novel/emerging PFAS. Three scenarios were developed, each reflecting varying levels of availability of empirical exposure and hazard data for a specific pollutant and indicating when modelled data need to be utilised. This scenario-based approach also demonstrated how the reliability of the resulting risk assessment decreases with an increasing reliance upon modelled data.

The SOS-ZEROPOL2030 risk assessment highlights substantial differences in data availability, exposure patterns, and hazard characterisation between legacy and novel PFAS in European marine environments. For PFOS and PFOA, exposure data are largely concentrated in the Greater North Sea, Norwegian Sea, Barents Sea, and Baltic Sea, where monitoring provides more than 100 datapoints per region. In contrast, the Mediterranean and Black Seas remain poorly characterised, with sparse or absent datasets. Available measurements span water, sediment, and biota compartments and are compiled from both monitoring programmes and scientific literature. While these exposure data provide important insights into where PFAS occur and at what concentrations, they do not indicate whether those concentrations are harmful to marine ecosystems. To assess this, information is needed on how sensitive different species are to PFAS exposure. One way to evaluate this is through species sensitivity distributions (SSDs), which are statistical models used to estimate concentrations of a stressor (like a chemical) that are safe for most species in an ecosystem. Although ecotoxicity data are available for a number of species exposed to PFOS and PFOA, the available evidence is still insufficient to construct robust SSDs. As risk assessment requires quantitative input data, an assessment factor (AF) approach was applied to derive hazard values for individual PFAS molecules. Predicted no-effect concentrations (PNECs) reflect the threshold concentration below which no adverse effects on species in the ecosystem are expected. PNECs of 0.4 ng/L for PFOS and 0.3 ng/L for PFOA were derived using this method. These values indicate very low toxicity thresholds in aquatic systems but also highlight the limitations of available PFAS hazard datasets for region-specific assessment.

Exposure data are similarly unevenly distributed for novel PFAS, with the most comprehensive datasets available for the Greater North Sea, Norwegian Sea, and Baltic Sea (>100 datapoints each) and major gaps persisting in the Mediterranean and Black Seas. Hazard data exist for 35 of 48 monitored novel PFAS compounds, but variability in data quality and completeness is substantial across European seas. Consequently, AF-based hazard characterisation produces PNECs spanning several orders of magnitude (0.4 ng/L to 108 µg/L), reflecting strong compound-specific variability and uncertainty. Overall, the integrated assessment shows that both legacy and novel PFAS risk characterisation is constrained by incomplete exposure coverage and limited toxicological datasets, particularly outside northern European seas.

3.2. High-Risk Areas and Hotspots

Risk assessment results indicate pronounced spatial variability in PFAS exposure and exceedance patterns across European seas (Ruhl et al., 2024; Maes et al., 2026). For PFOS, concentrations exceeded threshold values at 25% or more of sampling stations in the Adriatic Sea, Celtic Sea, and Western Mediterranean Sea, identifying these regions as key hotspots. For PFOA, threshold values were exceeded in 55% of observations across European seas, with elevated risk occurring across multiple northern and southern marine regions.

Novel PFAS generally show lower exceedance rates, with 14% of sampling stations exceeding threshold values in any individual sea region and an overall exceedance rate of approximately 8.5%. Nevertheless, elevated risk was observed in the Adriatic Sea, Greater North Sea, Baltic Sea, and North Atlantic, indicating that both industrialised and semi-enclosed marine environments are affected. Despite these identified hotspots, interpretation is constrained by uneven monitoring density. Northern European seas benefit from relatively dense datasets, whereas southern and eastern basins remain under-sampled. This introduces uncertainty in spatial comparisons and suggests that additional monitoring may further refine or alter current hotspot delineation.

3.3. Current Trends in PFAS Emissions

Current PFAS emission trends in the marine environment reflect a combination of legacy contamination, emerging chemical usage patterns, and continuing societal costs associated with PFAS pollution (Ruhl et al., 2024; Maes et al., 2026). Recent evidence highlights that PFAS pollution has wide-ranging impacts on human health and the environment, generating substantial economic burdens for society, including costs linked to disease, environmental remediation of contaminated water and soils, and disruption of ecosystem services. If current emission levels persist, long-term societal costs are projected to be extremely high. In contrast, early source reduction could substantially reduce these impacts, whereas relying solely on end-of-pipe treatment would be considerably more expensive over time (European Commission, 2026). This underscores the importance of early intervention, given the persistence of PFAS in both human populations and environmental compartments.

Legacy PFAS such as PFOS and PFOA continue to be detected despite regulatory phase-outs, indicating persistence, long-range transport, and ongoing secondary emissions from environmental reservoirs. Their continued presence, particularly in regions with historical industrial activity and waste inputs, clearly demonstrates the long-term environmental persistence of these compounds. At the same time, novel PFAS are increasingly detected across European marine systems, although at generally lower exceedance frequencies. The presence of 35 monitored compounds across multiple environmental matrices indicates expanding PFAS chemical diversity in the environment. However, strong variability in detection frequency and toxicity data suggests that monitoring is still in an early phase of development for many compounds.

Across both legacy and novel PFAS, a key trend is the persistence of spatial data gaps, particularly in the Mediterranean and Black Seas. These gaps limit the ability to assess temporal trends and to determine whether observed concentrations reflect increasing emissions, legacy contamination, or shifts in production and use patterns. Overall, the combined evidence suggests that while regulatory actions on PFOS and PFOA may have reduced direct emissions, environmental reservoirs and substitution with novel PFAS maintain ongoing input pressures. Continued expansion of monitoring coverage, alongside improved harmonisation of analytical methods, is essential to accurately resolve future emission trends and environmental trajectories.

3.4. Stakeholder Views: Understanding the PFAS Challenge

Key insights into the environmental challenges posed by PFAS were provided by a wide range of stakeholders through Living Labs organised within the framework of the SOS-ZEROPOL2030 project, addressing the Black Sea and the North-East Atlantic regions (Van Hulst et al., 2024a; Van Hulst et al., 2025). The Living Labs in the Black Sea region focused on the broader PFAS issue, while those in the North-East Atlantic region specifically addressed PFAS in medical applications as a concrete case study from which broader lessons on PFAS reduction and substitution could be drawn. The stakeholders' perspectives highlight critical knowledge gaps and practical concerns that complement the scientific findings of the SOS-ZEROPOL2030 risk assessment:

- **Persistence of PFAS in the Environment:** PFAS are highly persistent chemicals that remain in the environment long after release and are widely distributed across both the Black Sea and North-East Atlantic regions. They are consistently detected in water, sediment, and biota, demonstrating their persistence and accumulation across multiple environmental compartments. As they undergo limited natural degradation in marine environments, PFAS continue to accumulate over time, making them a long-term contamination issue that requires prevention-oriented management approaches.
- **Challenges in Understanding PFAS Transport Mechanisms:** Significant challenges remain in understanding how PFAS are transported from sources to marine environments in both the Black Sea and North-East Atlantic Sea. While it is known that PFAS can move through water, sediments, and biological pathways across the full product lifecycle, detailed knowledge of emission routes, environmental fate, and regional distribution is still limited. Major data gaps, uneven monitoring coverage, and insufficient analytical capacity hinder a full understanding of transport mechanisms. These limitations make it difficult to trace PFAS from source to sink, identify hotspots, or compare contamination patterns between regions with confidence.
- **Environmental Consequences of PFAS:** PFAS contamination poses risks to aquatic and marine ecosystems in both regions, primarily through long-term exposure and bioaccumulation in organisms. Their presence in water, sediment, and biota raises concerns about transfer through food webs and potential impacts on biodiversity, ecosystem functioning and human health. Although quantitative evidence for risks remains limited, a precautionary perspective is warranted due to the persistence and widespread distribution of PFAS. Combined with other environmental pressures, PFAS contribute to cumulative stress on marine ecosystems, reinforcing the need for improved monitoring and coordinated regional action.

4. The Policy and Regulatory Landscape

4.1. EU and European Regional Seas Level

The European Union has developed a multi-layered policy framework to address PFAS pollution, anchored in in the European Green Deal and its zero-pollution ambition, notably through the Chemicals Strategy for Sustainability (European Commission, 2020) and the Zero Pollution Action Plan (European Commission, 2021). These strategies aim to reduce environmental pollution to levels no longer considered harmful to human health and ecosystems, including a commitment to significantly reduce chemical pollution and associated risks by 2030.

In addition, the European Ocean Pact (European Commission, 2025), published in 2025, places further emphasis on reducing pollution in the marine environment. It prioritises targeted action on nutrient, plastic, chemical, and noise pollution, while strengthening marine governance, monitoring, and international cooperation—key elements for restoring the health of Europe's seas and achieving good environmental status. A central principle of the Ocean Pact is the source-to-sea approach to pollution management, which guides policy action by explicitly considering land-based sources of marine pollution. In the context of PFAS, this framework is particularly relevant, as PFAS are generated within land-based transport systems and subsequently transported via runoff and riverine pathways into marine environments, exemplifying the source-to-sea continuum addressed by the Pact.

Within this policy context, PFAS are widely recognised as a group of substances of high concern due to their persistence, mobility, and widespread occurrence in the environment, and are therefore subject to strengthening regulatory scrutiny and phased restrictions across multiple sectors (Devriese et al., 2023; Ruhl et al., 2024). EU regulatory action on PFAS is implemented through several complementary legislative instruments (Devriese et al., 2023; Devriese et al., 2025). At the core of EU chemicals management is REACH (European Parliament and Council, 2006), under which PFOS, PFOA, PFHxS, and other PFAS are already subject to restrictions, while a broad group restriction proposal covering thousands of PFAS is currently under evaluation.

Additional controls are provided through the EU Persistent Organic Pollutants (POPs) Regulation, which implements obligations under the Stockholm Convention (UNEP, 2001). Environmental protection frameworks, including the Water Framework Directive (WFD) (European Parliament and Council, 2000), the Environmental Quality Standards Directive (EQSD) (European Parliament and Council, 2008a), and the Marine Strategy Framework Directive (MSFD) (European Parliament and Council, 2008b), establish monitoring requirements and environmental quality objectives for priority substances, including selected PFAS. The revised Urban Wastewater Treatment Directive (UWWTD) sets the basis for the European Commission to develop a methodology for measuring PFAS in urban wastewater (European Parliament & Council of the European Union, 2024).

At the human health level, the European Food Safety Authority (EFSA) has set a tolerable weekly intake for a group of PFAS that accumulate in the body at 4.4 ng per kilogram of body weight (EFSA CONTAM Panel, 2020). Evidence indicates that most EU citizens are exposed to levels exceeding this threshold. Drinking water quality is regulated under the Drinking Water Directive (DWD), which sets thresholds of 0.1 μg/L for the sum of 20 PFAS or 0.5 μg/L for total PFAS, with these limits entering into force in 2026 (European Parliament and Council, 2020).

At the industrial level, the revised Industrial Emissions Directive (IED) strengthens monitoring and reporting requirements for PFAS emissions, including PFOA and PFHxS and their salts (European

Parliament and Council, 2024). More recently, the European Chemicals Industry Action Plan, published by the European Commission in 2025, sets out measures to strengthen the competitiveness of the EU chemicals sector while supporting innovation and sustainability, including actions to reduce PFAS emissions and promote the development of safer chemical alternatives (European Commission, 2025).

Recent PFAS risk assessments provide important scientific evidence to support implementation of these policy frameworks, particularly under the MSFD and WFD. However, significant regulatory and knowledge gaps remain. Current legislation does not yet fully address the diversity of PFAS, particularly novel and short-chain compounds, while information on PFAS occurrence in products, mixtures, and waste streams remains incomplete (Ruhl et al. 2024). In addition, conventional wastewater treatment systems are generally ineffective at removing PFAS, making prevention at source the most effective long-term management strategy (Maes et al., 2026). Addressing these challenges will require stronger upstream controls, improved transparency throughout supply chains, harmonised monitoring and analytical approaches, and closer integration of chemicals, water, product, and waste policies to support the EU's zero-pollution ambition.

At the regional seas level, PFAS governance is implemented through a combination of EU legislation and Regional Seas Conventions (Ruhl et al., 2024). Under the Oslo-Paris Convention (OSPAR), PFAS have only recently emerged as a priority issue. Although the 2023 Quality Status Report (OSPAR Commission, 2023) contains limited discussion of PFAS and focuses primarily on other marine pressures, PFOS has been monitored in biota since 2018 and in water since 2023. In 2022, PFAS were added to OSPAR's List of Chemicals for Priority Action (OSPAR Commission, 2022), with the list subsequently aligned with priority substances under REACH and the WFD. In addition, OSPAR has prioritised the monitoring of 24 PFAS compounds within its Coordinated Environmental Monitoring Programme, consistent with the requirements of the EQSD.

In the Black Sea region, the Bucharest Convention and its Protocol on the Protection of the Black Sea Marine Environment Against Pollution from Land-Based Sources and Activities do not explicitly address PFAS. Awareness of PFAS pollution remains limited, and dedicated monitoring and management measures are largely absent (Van Hulst et al., 2024a). Nevertheless, increasing attention is being given to PFAS through regional initiatives and ongoing efforts to strengthen monitoring and assessment capacities.

Under the Helsinki Convention (HELCOM), PFAS are addressed within the broader framework for hazardous substances. PFOS and other regulated PFAS are included in regional monitoring and assessment activities supporting implementation of the Baltic Sea Action Plan (HELCOM, 2023). HELCOM has recognised PFAS as contaminants of emerging concern and has highlighted the need for improved monitoring, harmonised assessment methodologies, and enhanced knowledge generation. However, comprehensive regional management measures targeting PFAS as a substance group have not yet been established.

Similarly, under the Barcelona Convention, PFAS are addressed indirectly through the broader framework for hazardous substances and land-based sources of pollution. While PFAS are not currently the subject of dedicated regional measures, the Convention's monitoring and pollution-control activities provide mechanisms through which PFAS can be assessed and managed alongside other chemical contaminants. As concern over PFAS continues to grow, further integration of PFAS-specific monitoring and management approaches within regional sea conventions will be important to support coordinated action across European marine environments.

4.2. National Level

At the national level, several EU Member States have taken proactive steps to restrict PFAS use or accelerate phase-outs ahead of EU-wide measures. France has introduced national restrictions on certain PFAS uses in consumer products and is advancing broader phase-out policies, while countries such as Denmark, Sweden, the Netherlands, and Germany have been particularly active in proposing or supporting group-based PFAS restrictions under REACH and strengthening national monitoring programmes (Devriese et al., 2023; Ruhl at al., 2024). These frontrunner countries have also invested in improved analytical capacity and source identification, particularly in relation to industrial emissions, wastewater treatment plants, and contaminated sites.

Implementation of EU water and environmental quality standards at the national level has led to expanded monitoring of PFAS in surface water, groundwater, drinking water, and biota. Many countries are now aligning their monitoring programmes with emerging EU thresholds, including the Drinking Water Directive limits for total PFAS and the sum of PFAS. However, enforcement and compliance approaches differ, particularly regarding industrial discharge permits and remediation obligations for contaminated sites. Despite these advances, significant disparities remain across Europe. Some Member States have limited monitoring capacity, fewer resources for analytical testing, and less developed inventories of PFAS sources and emissions. This results in uneven data availability and challenges for cross-border comparison and basin-scale risk assessment. To address these gaps, there is increasing emphasis on harmonising monitoring methods, improving reporting requirements, and strengthening cooperation through EU agencies and regional sea conventions.

Table 4-1. Summary of main EU policy actions on PFAS (Source: https://environment.ec.europa.eu/topics/chemicals/pfas-pollution_en)

Policy area	Policy action	Key measure/ requirement	Timeline/status
Chemicals	Proposed EU-wide PFAS restriction under REACH	Broad restriction of all PFAS (group approach instead of substance-by-substance regulation); based on ECHA evaluation and Commission proposal	Proposal submitted in 2023; Commission will follow ECHA opinion
Industrial emissions	Industrial Emissions Directive (IED)	Stricter monitoring and reporting of PFAS emissions, including PFOA and PFHxS and their salts	Reporting obligations from 2028
Drinking water	Drinking Water Directive (DWD)	Mandatory monitoring of PFAS in all drinking water and compliance with limit values for total PFAS and sum of PFAS	Applies from January 2026
Surface water & groundwater	Water pollution update framework	Updated list of priority substances to ensure alignment with scientific evidence; strengthens monitoring and control of emerging contaminants	Adopted in 2026

Policy area	Policy action	Key measure/ requirement	Timeline/status
Soil	Soil Monitoring Law	PFAS included in list of soil contaminants; mandatory measurement in relevant soils to identify contamination hotspots	Ongoing implementation under EU soil monitoring framework
Packaging	Packaging and Packaging Waste Regulation	Ban on food-contact packaging containing PFAS above set concentration limits	Applies from August 2026

5. The SOS-ZEROPOL2030 Transition Pathway for Reducing PFAS within the Zero Pollution Action Plan

5.1. Overview

Within the scope of SOS-ZEROPOL2030, a Strategic Zero Pollution Framework and associated Roadmap have been developed, defining objectives, targets, actions, and timeframes to support the achievement of the EU Zero Pollution ambition for a toxic-free environment. The two SOS-ZEROPOL2030 objectives that correspond to actions explicitly linked to PFAS focus on stimulating innovation in sustainable chemicals, ingredients, processes, and products, as well as promoting the use of safer alternatives. In addition, broader chemical policy objectives developed by SOS-ZEROPOL2030 are also relevant, including harmonising monitoring of the most harmful substances; improving transparency throughout the value chain; promoting a transformative shift towards a sustainable, circular, and climate-neutral EU industry; and increasing public awareness of hazardous substance exposure. These objectives are translated into targets and actions, as illustrated by the example in Table 5-1. Together, these elements operationalise the transition pathway for PFAS and underpin the sector-specific actionable guidance presented in the following sections.

The Framework and Roadmap were developed through a co-design approach that integrates outputs from the SOS-ZEROPOL2030 project and aligns them with the objectives of the EU Zero Pollution Action Plan. Multi-stakeholder engagement is central to this process and is both informed by and contributes to data, evidence, and analytical outputs, as well as to the definition of pollution reduction, prevention, mitigation, and monitoring measures. This ensures coherence between scientific evidence, stakeholder input, and policy objectives under the Zero Pollution framework.

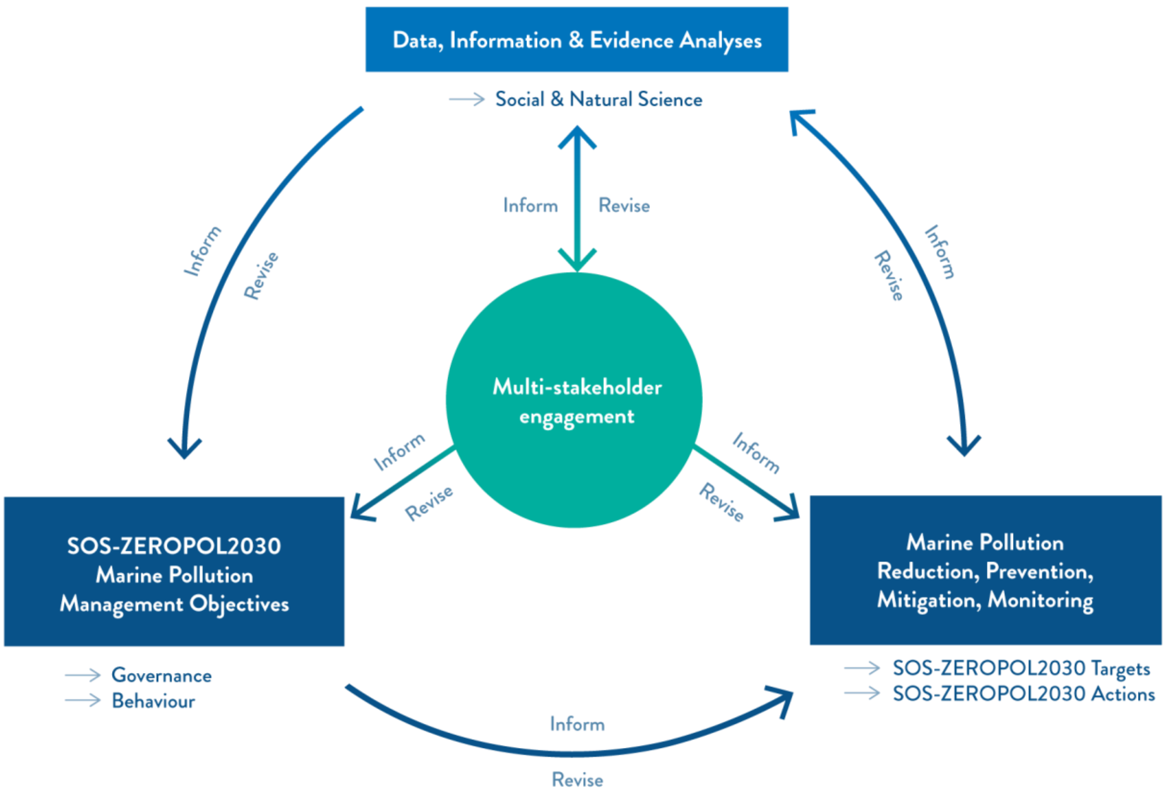

Figure 5-1. The Co-Design Approach of the SOS-ZEROPOL2030 Project.

Table 5-1. Example of SOS-ZEROPOL2030 objectives, targets and actions related to PFAS to support the EU Zero Pollution ambition for a toxic-free environment.

Objective	Target	Timeframe	Action
Stimulate innovation of sustainable chemicals, ingredients, processes, and products.	By 2030, the EU establishes a support programme for the development of wastewater treatment plants for emerging industrial practices that are expected to grow in Europe.	short-term	Develop technology to concentrate hazardous substances, such as PFAS, to enhance the effectiveness of removal and remediation from large water quantities such as streams in wastewater treatment plants.
Promote uses of safer alternatives	Phase out the manufacturing, import, and use of most harmful substances, including all PFAS to significantly decrease the input of hazardous substances into the natural environment.	medium-term	Start with phasing out hazardous substances in non-essential uses.
		medium-term	Create clear guidelines for judgement of essentiality and verify these by stakeholder consultation.
		medium-term	Ensure that future development of active substances used in biocides, plant protection products and medicinal products adheres to afe and Sustainable by Design (SSbD) approaches, similar to substances that fall under REACH.
		medium-term	Invest public funds into development of SSbD alternative chemicals and materials, both for basic research as well as applied research.
	18 months after entry into force of the PFAS restriction proposal, companies that make use of a derogation for PFAS use for a specific application, need to invest a specific percentage of their revenue to develop alternatives.	short-term	Following the reporting approach included in the PFAS restriction proposal on the continued use of PFAS under a specific derogation, the EU integrates reporting obligations on the progress companies make towards developing alternatives.

5.2. Limitations and scope considerations

It should be highlighted that the measures presented in this guidance should not be interpreted as a sequential implementation plan. Rather, they represent complementary interventions that operate across different stages of the source-to-sea continuum and are expected to collectively contribute to the reduction of PFAS emissions and environmental exposure. Their effectiveness depends on coordinated and parallel action across governance levels and stakeholder groups, rather than a fixed order of implementation. In addition, the socio-economic dimension of the proposed measures is not quantified in this work. Information on implementation costs, technical feasibility, cost-effectiveness, and distributional impacts across stakeholder groups remains limited in the current evidence base, particularly for emerging technologies. Evidence from PFAS-related economic assessments suggests that the costs of inaction can be substantial, including significant societal burdens linked to human health impacts and ecosystem service losses, while mitigation scenarios may involve considerable but variable investment costs depending on the level of regulatory ambition. However, such cost–benefit relationships remain highly uncertain for many emerging pollutants and mitigation technologies, and are not yet systematically quantified across the full range of policy options. This represents an important limitation and highlights the need for further research to better understand the operational and economic implications of implementing these measures to support evidence-based decision-making and prioritisation of mitigation options within the Zero Pollution Action Plan framework.

Source-to-Sea Pathways of PFAS

Figure 5-2. Conceptual source-to-sea pathways of PFAS.

6. Policy and Regulatory Measures

6.1. Introduction

Despite growing EU action under REACH and the Chemicals Strategy for Sustainability, important gaps remain in the governance of PFAS in relation to the EU's zero pollution ambition (Devriese et al., 2023). Recent proposals for a universal, group-based restriction, rather than regulating individual substances one by one, reflect a broader shift towards preventing pollution at its source and addressing PFAS impacts throughout their entire life cycle. However, implementation is constrained by contested operationalisation of the "essential use" and SSbD concepts, regulatory and data limitations, and significant power asymmetries between industry and public authorities (Van Leeuwen et al., 2023). Fragmentation across governance frameworks and the continued presence of legacy PFAS in the environment further challenge the effectiveness of current approaches. Below, a set of policy- and regulatory-related recommendations is presented as actionable guidance for EU policymakers, though many of these measures are also relevant and useful for policy development at the European Regional Seas Conventions level (Van Hulst et al., 2024; Kopke et al., 2026).

6.2. Actionable Guidance

Strengthening PFAS Source Control and Substitution

- Support the adoption and implementation of a group-based PFAS restriction under REACH, currently under evaluation by ECHA's scientific committees, incorporating time-bound phase-outs and a progressively operationalised essential-use approach to define and limit derogations to prevent continued substitution of regulated PFAS with unregulated analogues. (▲ Source Control)
- Progressively operationalise the essential-use concept across relevant EU product and sector legislation (e.g. medical, industrial, consumer products), ensuring harmonised criteria for determining when PFAS use is justified and prioritise elimination of non-essential PFAS uses. (▲ Source Control)
- Strengthen eco-design requirements under the Ecodesign for Sustainable Products Regulation (ESPR) to progressively eliminate PFAS from new products, prioritising high-emission sectors such as textiles, medical devices, coatings, and packaging. (▲ Source Control)
- Expand substitution policies and innovation incentives (e.g. Horizon Europe, LIFE programme) to accelerate development, testing, and market uptake of safer PFAS alternatives, with early-stage regulatory support for approval pathways. (▲ Source Control)

Managing PFAS Across Product Lifecycles and Circular Systems

- Integrate PFAS considerations into circular economy and waste policy frameworks to reduce the risk of recycling-driven reintroduction of PFAS into secondary materials. (▲ Source Control)
- Develop EU guidance for safe management and treatment of PFAS-containing waste, prioritising destruction or irreversible treatment methods where recycling is not environmentally safe. (● End-of-Pipe Management)

- Embed PFAS-free criteria into green public procurement, eco-labels, and product passport systems to drive upstream substitution and market transformation. (■ Process Control)
- Promote true-cost accounting approaches in policy and procurement frameworks to better reflect environmental and health externalities associated with PFAS use. (■ Process Control)

Monitoring, Transparency and Supply Chain Control

- Strengthen REACH reporting and disclosure requirements to improve transparency on PFAS content in mixtures and articles, and enhance identification of complex PFAS, including polymers and precursors, where analytically and regulatory feasible. (◙ Enabling Control)
- Expand and harmonise EU-wide PFAS monitoring across water, soil, air, biota, and selected products, building on existing MSFD, WFD, and Drinking Water Directive frameworks and emerging soil and chemical monitoring initiatives. (◙ Enabling Control)
- Develop and implement Digital Product Passports under the ESPR framework, progressively integrating PFAS composition data where relevant to improve traceability, enforcement, and procurement decision-making (◙ Enabling Control)
- Extend monitoring frameworks to include novel, short-chain, and precursor PFAS, supported by progressively harmonised analytical methods to improve comparability, coverage, and completeness. (◙ Enabling Control)

Environmental Regulation and Risk Management

- Accelerate the integration of PFAS into environmental quality standards and groundwater legislation, including group-based threshold approaches where scientifically feasible. (◙ Enabling Control)
- Strengthen implementation of the Industrial Emissions Directive (IED through improved monitoring and reporting obligations for PFAS emissions in relevant sectors. (◙ Enabling Control)
- Improve coherence between REACH, WFD, and MSFD frameworks, ensuring consistent responses when environmental thresholds or risk indicators are exceeded. (◙ Enabling Control)
- Develop risk-based spatial prioritisation tools to support targeted monitoring, remediation, and regulatory action in PFAS hotspot regions. (◙ Enabling Control)

7. Technological Measures

7.1. Introduction

There is already a wide range of technological measures for preventing, reducing, and mitigating PFAS and this this range is expected to expand further in the near future (Ruhl et al., 2024). Their effective implementation requires close collaboration across all relevant stakeholders. Some solutions are readily available and can be implemented immediately, while others remain under development and require further research, testing, and validation. Key uncertainties include the behaviour, transport, and transformation of different PFAS across environmental media, including variability in partitioning, precursor degradation pathways, and long-range transport potential. Additional uncertainties relate to the effectiveness, scalability, and long-term environmental performance of emerging treatment and destruction technologies. Below, technological solutions and their corresponding actionable guidance are organized by the key stakeholder groups responsible for implementing them.

7.2. Actionable Guidance

7.2.1. Industry actors

Elimination of non-essential PFAS uses in product design

- Identify and eliminate PFAS in applications that are not essential for health, safety, or critical societal functioning, in line with EU essential-use criteria. (▲ Source Control)
- Redesign products using functional substitution principles, focusing on coatings, textiles, paper treatments, consumer goods, and medical applications where PFAS properties are not strictly required. (▲ Source Control)
- Prioritise validated safe non-PFAS alternatives and systematically phase out PFAS in applications where performance trade-offs are acceptable. (▲ Source Control)
- Embed essential-use screening into R&D pipelines and procurement to ensure PFAS is only retained where no viable alternative exists. (▲ Source Control)

Controlled use and emission minimisation for essential applications

- Apply Best Available Techniques (BAT) in PFAS production and use where PFAS remains essential (e.g. medical, selected industrial applications). (■ Process Control)
- Implement advanced emission control systems (activated carbon, flue gas oxidation, wastewater treatment, stack monitoring) to minimise releases across all life-cycle stages. (■ Process Control & ● End-of-Pipe Management)
- Redesign processes to reduce fugitive emissions and prevent unnecessary losses of PFAS intermediates. (■ Process Control)
- Require monitoring and transparent reporting for all essential-use PFAS production and handling sites. (◙ Enabling Control)
- Avoid in-situ formation of PFAS during industrial or chemical processes when alternative methods exist that do not produce PFAS. (■ Process Control)

Transition away from PFAS-dependent industrial processes

- Transition fluoropolymer production toward fluorosurfactant-free or alternative processing aid systems where technically feasible or invest in the development and scaling of alternative production routes. (▲ Source Control)
- Support the gradual replacement of fluorinated refrigerants and other PFAS-containing gases through equipment redesign, refrigerant recovery, and adoption of lower-emission alternatives during normal asset replacement cycles. (▲ Source Control)
- Phase out PFAS-based processing aids and lubricants, including legacy surfactants, in industrial applications such as plastics production. (▲ Source Control)
- Evaluate and redesign systems to enable long-term replacement of PFAS-dependent functionalities (e.g. sealing materials, equipment linings) during equipment renewal cycles. (▲ Source Control)
- Ensure substitution strategies avoid "regrettable substitution" with equally persistent or hazardous chemicals. (◙ Enabling Control)

Minimize PFAS emissions from end-of-life products

- Separate PFAS-containing waste streams from non-PFAS waste to enable targeted yet efficient destruction of PFAS-containing materials. (■ Process Control)
- Ensure destruction of PFAS-containing waste in well-designed and properly operated facilities with verified mineralisation efficiency. (■ Process Control)
- Prevent landfilling and environmental leakage of PFAS-containing sludge from wastewater treatment and of waste from essential-use applications. (■ Process Control)
- Install capture and adsorption systems at facilities handling PFAS to prevent emissions into air and water. (● End-of-Pipe Management)

Improve monitoring and transparency in reporting

- Implement harmonised PFAS monitoring systems across production, use, end-of-life stages to track and minimise emissions from products containing PFAS. (◙ Enabling Control)
- Adopt "total PFAS" screening methods (e.g. CIC-based approaches) to complement targeted chemical analysis. (◙ Enabling Control)
- Support development of EU-wide essential-use registries linked to emission reporting systems. (◙ Enabling Control)

7.2.2. Researchers/Academics

Assessment and decision-support frameworks for PFAS management

- Develop robust methodologies to operationalise EU essential-use criteria at product and process level. (◙ Enabling Control)
- Create decision-support tools under a SSbD framework that integrate hazard, exposure, functional performance, and societal relevance. (◙ Enabling Control)

Substitution safety and regrettable replacement prevention

- Evaluate alternatives not only for performance but also persistence, mobility, and long-term toxicity. (◙ Enabling Control)
- Build transparent and where possible, openly accessible comparative datasets of PFAS and non-PFAS alternatives to support informed substitution and avoid regrettable substitutions. (◙ Enabling Control)
- Study real-world substitution cases to identify systemic drivers of regrettable substitution. (◙ Enabling Control)

Emissions, fate and system-wide PFAS accounting

- Quantify PFAS flows across essential, non-essential, and transitional uses. (◙ Enabling Control)
- Improve understanding of long-term environmental persistence and transformation to PFAAs. (◙ Enabling Control)
- Identify high-emission hotspots linked to essential-use exemptions and industrial clusters. (◙ Enabling Control)

Treatment technologies for essential-use residuals

- Develop scalable technologies for the safe destruction of Per- and polyfluoroalkyl substances (PFAS) in highly contaminated waste streams, particularly those arising from essential-use sectors. (● End-of-Pipe Management)
- Develop and optimise PFAS concentration technologies that reduce treatment volumes and improve the effectiveness of subsequent destruction processes. (● End-of-Pipe Management)
- Assess the efficiency and effectiveness of incineration processes and optimise their performance under realistic industrial waste compositions. (◙ Enabling Control)

7.2.3. Infrastructure and Service Providers

Capture and control of essential-use emissions

- Install PFAS capture systems at facilities handling essential-use applications. (● End-of-Pipe Management)
- Evaluate and deploy PFAS-specific treatment technologies (e.g. ion exchange, adsorption, nanofiltration) at wastewater treatment facilities where source control alone cannot sufficiently reduce emissions. (● End-of-Pipe Management)
- Implement continuous emission monitoring systems for regulated essential-use PFAS streams. (◙ Enabling Control)

Waste and destruction infrastructure for essential-use residues

- Prioritise controlled destruction of PFAS waste from essential-use applications, using proven effective and efficient methods. (● End-of-Pipe Management)
- Avoid environmental dispersal routes (land application, uncontrolled landfill) for essential-use PFAS residues. (■ Process Control)

- Develop integrated waste sorting systems that identify PFAS-containing materials for targeted treatment. (■ Process Control)

Monitoring infrastructure and system support

- Support environmental monitoring networks targeting PFAS emissions from essential-use sectors. (◙ Enabling Control)
- Enable data integration between infrastructure operators, regulators, and researchers for PFAS flow tracking. (◙ Enabling Control)
- Provide operational transparency for PFAS handling in critical infrastructure sectors. (◙ Enabling Control)

8. Social Engagement Measures

8.1. Introduction

Tackling PFAS is not only a technological and regulatory challenge but also a societal one. Reducing PFAS emissions requires engagement across the entire value chain, from manufacturers and product designers to policymakers, researchers, waste managers, and consumers. While awareness of PFAS has increased in recent years, knowledge of their widespread use, environmental persistence, and potential impacts remains limited. In addition, decisions to phase out or substitute PFAS often involve trade-offs related to product performance, costs, convenience, and the availability of suitable alternatives.

Social engagement measures can support the transition towards reduced PFAS use by increasing awareness, improving understanding of the essential-use concept, and encouraging the adoption of safer alternatives where feasible. They can also facilitate acceptance of product redesigns, changes in consumption patterns, and improved waste management practices. Some actions can be implemented immediately through communication, education, and training initiatives, while others require longer-term changes in organisational practices and societal expectations. Below, actionable guidance is organised according to key stakeholder groups responsible for implementing social engagement initiatives.

8.2. Actionable Guidance

8.2.1. Policymakers

Integrate PFAS awareness into public communication and education systems (◙ Enabling Control)

- Develop targeted public awareness campaigns to address low societal awareness of PFAS, focusing on their sources, environmental pathways, potential risks, and measures to reduce exposure and emissions.
- Enhance and expand the coverage of chemical pollution topics in school curricula, public health communication, and environmental education programmes to improve societal literacy on harmful chemicals such as PFAS and promote safer alternatives and practices that reduce use and environmental release.

Promote behavioural change and reduction of non-essential PFAS use (◙ Enabling Control)

- Launch public initiatives to encourage the reduction of non-essential uses of PFAS and promote safer alternatives in everyday applications, such as packaging, textiles, and household goods.
- Encourage behavioural change campaigns linked to consumption choices, waste handling, and pollution prevention at household level.

Strengthen governance visibility and societal trust (◙ Enabling Control)

- Communicate clearly about PFAS regulatory developments, monitoring efforts, and emerging hotspots once identified to increase transparency and public trust.
- Ensure PFAS becomes part of broader marine and water governance agendas to raise its political and societal visibility.

8.2.2. Industry Actors

Improve transparency and public communication on PFAS use (◙ Enabling Control)

- Provide clear, accessible information on PFAS content in products, production processes, and emission pathways across supply chains.
- Integrate Digital Product Passports under the ESPR as a transparency tool for reporting chemical content, including PFAS, across product life cycles to support informed decisions by consumers, businesses, and regulators.
- Develop standardised disclosure mechanisms to report the use and release PFAS throughout supply chains, including importers and downstream users, to improve transparency and support informed decision-making by regulators, businesses, and the public.

Support societal trust through accountability mechanisms (◙ Enabling Control)

- Introduce public reporting systems on PFAS reduction efforts, substitution progress, and emissions control measures to increase accountability and market pressure.
- Establish recognition mechanisms ("name and praise") for companies actively reducing or eliminating PFAS use and adopting safer alternatives.

8.2.3. Researchers and Academics

Translate PFAS science into accessible societal knowledge (◙ Enabling Control)

- Produce simplified, publicly accessible summaries explaining the sources of PFAS, how they spread through the environment, their potential risks, and key uncertainties in current scientific knowledge.
- Support the development of communication tools (factsheets, visualisations, scenario tools) that can be used by policymakers, NGOs, and educators.

Support participatory and applied knowledge generation (◙ Enabling Control)

- Engage in co-production of knowledge with stakeholders through Living Labs and other participatory research formats to improve societal relevance of PFAS data.

8.2.4. NGOs and Civil Society Organizations

Lead public awareness and behavioural change initiatives (◙ Enabling Control)

- Organise campaigns, workshops, and community events to raise awareness of PFAS, their potential impacts on health and the environment, and practical ways to reduce exposure and emissions in everyday life.
- Promote community-level actions to reduce non-essential uses of PFAS and support the adoption of more sustainable products and practices.

Mobilise community engagement and citizen participation (◙ Enabling Control)

- Support participatory monitoring and citizen science initiatives to improve public understanding of PFAS presence in the environment.
- Encourage local engagement networks to connect communities across sea basins for shared learning and advocacy.

Act as intermediaries in multi-stakeholder dialogue (◙ Enabling Control)

- Facilitate communication between policymakers, industry, and the public to ensure PFAS governance measures are understood and socially supported.
- Advocate for inclusion of PFAS issues in regional governance and funding agendas, helping translate technical priorities into societal action.

9. Key Takeaways

PFAS are a large and diverse group of highly persistent chemicals widely used in industrial processes and consumer products across multiple sectors, contributing to their widespread occurrence in the environment. Their extensive use, persistence, and continued release from both historical and ongoing sources make PFAS pollution a complex, long-term challenge in European seas, particularly in regions where monitoring data and scientific understanding remain limited. Addressing this challenge requires action across the entire life cycle of these substances, rather than relying on single-point interventions. This includes preventing emissions at the source, improving industrial processes, reducing releases through waste and wastewater treatment, and strengthening the policies, monitoring systems, and governance frameworks needed for effective long-term management.

Addressing this challenge begins with preventing PFAS from entering the environment. This requires regulatory measures under REACH that restrict groups of PFAS rather than individual substances, alongside the progressive implementation of the essential-use concept and strengthened eco-design requirements under the ESPR. Together, these measures can reduce unnecessary PFAS use, promote safer alternatives, and avoid regrettable substitution. Where PFAS use cannot yet be eliminated, emissions should be minimised through improved industrial practices, effective containment systems, the application of BAT, and measures to prevent the unintentional formation of PFAS during manufacturing. For legacy contamination and unavoidable releases, advanced treatment and destruction technologies are required, particularly for highly contaminated aqueous waste streams. Measures should also be taken to prevent PFAS from reaching the environment via wastewater effluent, sewage sludge, and landfill leachate.

The success of these measures depends on robust supporting systems. These include harmonised monitoring of PFAS in water, sediments, biota, and other environmental compartments; improved chemical disclosure and reporting under REACH; and enhanced supply chain traceability through emerging tools such as Digital Product Passports. Identifying pollution hotspots and prioritising action where risks are greatest using spatial prioritisation and risk-based assessment frameworks will also help target resources more effectively. In addition, greater alignment across EU water, chemicals, and industrial emissions legislation is needed to ensure a coherent and effective approach to PFAS management.

Alongside regulatory and technical measures, improved transparency and communication across supply chains, increased public awareness, and active stakeholder engagement can help build societal support for reducing PFAS use and adopting safer alternatives. Effective implementation will also depend on a clearer understanding of the socio-economic implications of proposed measures, including their costs, feasibility, wider societal impacts, and distributional trade-offs (i.e. how costs, benefits, and risks are distributed across different societal groups, regions, and economic actors). At present, these aspects remain insufficiently quantified, understood, and documented within the current evidence base.

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List of Abbreviations

Abbreviation	Full Term
ADONA	Ammonium 4,8-dioxa-3H-perfluorononanoate
AF	Assessment Factor
BAT	Best Available Techniques
CIC	Combustion Ion Chromatography
DWD	Drinking Water Directive
EEA	European Economic Area
EFSA	European Food Safety Authority
EPA	Environmental Protection Agency (USA)
EQSD	Environmental Quality Standards Directive
ESPR	Ecodesign for Sustainable Products Regulation
EU	European Union
F-53B	Chlorinated polyfluoroalkyl ether sulfonate (trade name mixture)
FTOHs	Fluorotelomer alcohols
FTS	Fluorotelomer sulfonates
HELCOM	Helsinki Commission (Baltic Marine Environment Protection Commission)
HFPO-DA	Hexafluoropropylene oxide dimer acid (GenX)
IED	Industrial Emissions Directive
LIFE	EU LIFE Programme
MSFD	Marine Strategy Framework Directive
OECD	Organisation for Economic Co-operation and Development
OSPAR	Oslo-Paris Convention for the Protection of the Marine Environment of the North-East Atlantic
PAPs	Polyfluoroalkyl phosphate esters
PFAS	Per- and polyfluoroalkyl substances

Abbreviation	Full Term
PFBA	Perfluorobutanoic acid
PFBS	Perfluorobutanesulfonic acid
PFECAs	Perfluoroether carboxylic acids
PFHxA	Perfluorohexanoic acid
PFHxS	Perfluorohexane sulfonic acid
PFNA	Perfluorononanoic acid
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctane sulfonic acid
PFPeA	Perfluoropentanoic acid
PFPrA	Perfluoropropionic acid
PNEC	Predicted No-Effect Concentration
POPs	Persistent Organic Pollutants
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
SSbD	Safe and Sustainable by Design
SWOT	Strengths, Weaknesses, Opportunities, Threats analysis
TFA	Trifluoroacetic acid
WFD	Water Framework Directive
WWTP	Wastewater Treatment Plant
ZPAP	Zero Pollution Action Plan

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