

**Jean Schmitt*,
Gudrun Lettner**

Summary

Per- and polyfluoroalkyl substances (PFAS) possess remarkable properties that make them attractive for many applications, including non-stick coatings, waterproof clothing, and firefighting foams. However, this is a double-edged sword: their thermal and chemical resistance also means that they do not degrade easily once released into the environment. Consequently, PFAS are now regularly detected in even the most remote regions of the planet. They are found in blood samples of humans and wildlife, and are associated with a wide range of adverse health outcomes: PFAS have been shown to weaken the immune system, interfere with foetal development, disrupt endocrine function and increase cancer risk.

While some PFAS are restricted in many countries, they continue to accumulate in the environment and will persist for decades, contaminating food and water. Their removal from the environment has been estimated to cost €2 trillion in Europe, with recurring annual costs of €100 billion to mitigate future emissions. Beyond these enormous mitigation costs, PFAS-related health impacts will impose societal costs amounting to tens of billions of euros annually.

Regulatory efforts currently focus on reducing PFAS production and use, and on limiting exposure by setting maximum concentrations in water and food. However, millions of molecules fall under the PFAS definition, and around 1,400 are currently used in industrial applications, making comprehensive toxicological and environmental assessments a daunting challenge.

Strict regulation is urgently needed to phase out PFAS as rapidly as possible, while allowing for time-limited, sector-specific derogations for applications that deliver clear societal benefits and currently lack safer alternatives. This must be accompanied by increased support for the development and deployment of safer substitute materials.

* Corresponding author

PFAS

Understanding and Addressing the Global Pollution Crisis

Introduction

Per- and polyfluoroalkyl substances (PFAS), also known as forever chemicals, are a class of synthetic organic chemicals with at least one carbon-fluorine bond, among the strongest single bonds in organic chemistry. The Organisation for Economic Co-operation and Development (OECD) gives a widely accepted and complete definition of PFAS compounds.¹ As of January 2026, 7.3 million molecules are listed as PFAS in the PubChem database.

Their chemical structure confers high thermal and chemical stability, making PFAS attractive for a wide range of applications. However, this property is double-edged: PFAS are environmentally persistent, degrade very slowly and accumulate over long timescales in soil, water, and living organisms, including humans. Efforts to degrade PFAS and remove them from the environment focus on breaking the carbon-fluorine bond – a costly and energy-intensive process, currently challenging to deploy at a large scale.²

PFAS are also water-, oil-, and dust-repellent, making them ideal for protective coatings. How-

ever, once released into the environment, they become highly mobile and difficult to remove from polluted water and soil.

Approximately 1,400 PFAS are used in more than 200 industrial applications,³ including the energy sector, medical devices, consumer products, and semiconductors. Specifically, PFAS are used in high-resistance wind turbine coatings, batteries, lubricants, waterproof and high-performance textiles, cosmetics, non-stick cookware coatings, pesticides, fire-extinguishing foams, and food packaging. PFAS are also used in cooling devices and heat pumps. With the rapid expansion of data centres driven by advances in artificial intelligence, these facilities may become a significant source of PFAS in the future.⁴

PFAS are important components of many advanced materials, some of which are critical for applications in the medical sector and for the energy transition. Yet their widespread use has harmful health and environmental consequences. The PFAS case highlights the need for tools to guide innovation in advanced materials amid high uncertainty about potential negative impacts.

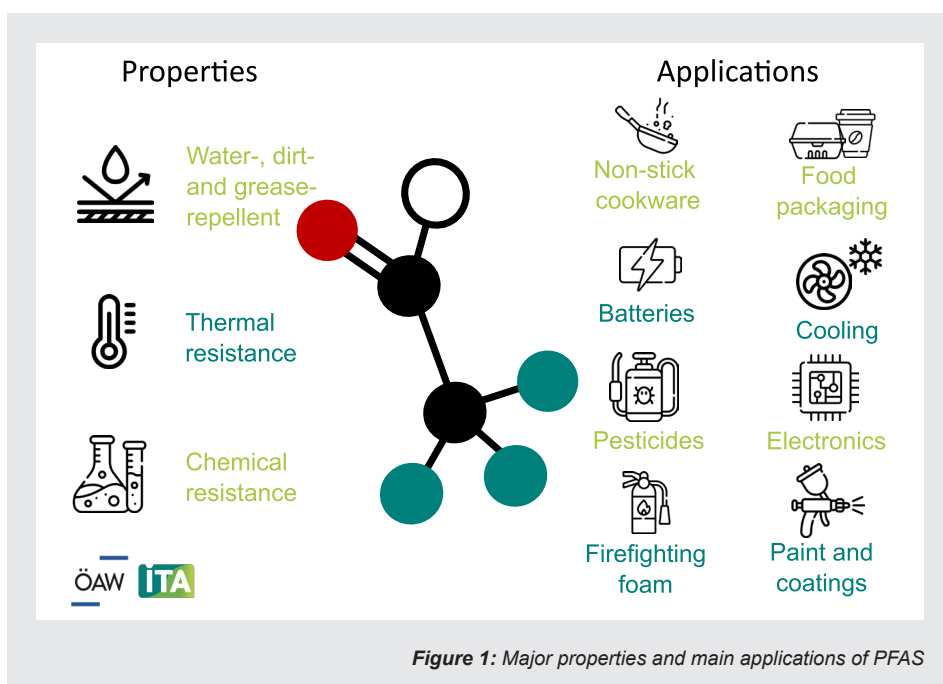


Figure 1: Major properties and main applications of PFAS

Legacy PFAS

PFAS have been used industrially since the 1940s, and concerns about their environmental persistence and potential health impacts emerged as early as the 1950s, triggering efforts to regulate them and limit their use.⁵ The term *legacy PFAS* generally refers to phased-out compounds and typically includes four molecules and their derivatives: Perfluorooctanoic acid (PFOA), Perfluorooctanesulfonic acid (PFOS), Perfluorohexanesulfonic acid (PFHxS), and Perfluorononanoic acid (PFNA).

PFOS and PFOA were among the first PFAS introduced at an industrial scale, notably in waterproof textiles and firefighting foams.⁶ They were detected in environmental samples and in human blood samples in the 1970s and 1980s.⁷ In the 1990s, evidence of their carcinogenic effects among exposed workers began to emerge.⁸

As evidence of their toxicity accumulated, the European Union restricted the use of PFOS in 2006⁹ and PFOA in 2020.¹⁰ Both substances are listed under the *Stockholm Convention on Persistent Organic Pollutants*, which strictly regulates the production, trade, and use of persistent organic pollutants. PFHxS, initially introduced as a substitute for PFOS, was added to the Convention in 2022 following growing concerns about its toxicity. They are restricted in the EU under Regulation 2019/1021 on persistent organic pollutants (*POPs Regulation*). Those four chemicals have been widely investigated and are typically regulated together in the EU.

As a result of these regulatory measures, blood concentrations of legacy PFAS have declined over the past decades: PFOS levels decreased by 85 % between 1999 and 2018, and PFOA levels by 70 %, underscoring the effectiveness of

regulatory action.¹¹ However, legacy PFAS still account for a large share of PFAS detected in environmental and human blood samples.¹² Measurements show their presence in more than 99 % of the population worldwide,¹³ and they have been detected in wildlife across the globe, from Antarctic penguins to Arctic seals and polar bears.^{14,15} In October 2025, 24 EU leaders from 19 countries tested positive for three to eight PFAS in blood samples; half of them showed concentrations associated with potential adverse health effects.¹⁶

The environmental persistence of PFAS and their slow elimination from the human body mean that these substances will continue to pose health risks for decades, even after being banned. In addition, some non-regulated PFAS can degrade into PFOS, PFOA, and other problematic molecules.¹⁷ Furthermore, concentrations of other PFAS used as alternatives to restricted chemicals (also referred to as *emerging PFAS*) are increasing, despite limited understanding of their long-term toxicity and health effects.^{18,19}

Health impacts of PFAS

Although the acute toxicity of PFAS is generally low, they accumulate in the human body, and chronic exposure to even low concentrations has been shown to cause a wide range of adverse health impacts (Figure 2). PFAS accumulate primarily in the blood and organs such as the liver, kidneys, and adipose tissue.²⁰

PFAS can impair immune function,²¹ reducing the body's ability to fight infections and diminishing the effectiveness of certain vaccines. This particularly affects children and individuals with weaker immune systems. PFAS also interfere with the endocrine system, leading to metabolic disturbances and increased risks of developing

type 2 diabetes.^{7,22} While the role of PFAS exposure in specific diseases (e.g., renal cancer) is still debated, evidence of their negative health impacts is accumulating.

To date, most toxicological studies have focused on a small number of molecules, primarily legacy PFAS. However, the recent development of alternative substances has led to the introduction of thousands of new PFAS, for which toxicological data remains scarce. In addition, the health effects of combined exposure to multiple PFAS are still poorly understood.²³

The elimination of PFAS from the human body (their toxicokinetics) depends strongly on their chemical structure. Their biological half-life, the time required for the PFAS concentration to decrease by half in the body, assuming no new intake through water or food, can reach several years (Figure 3).

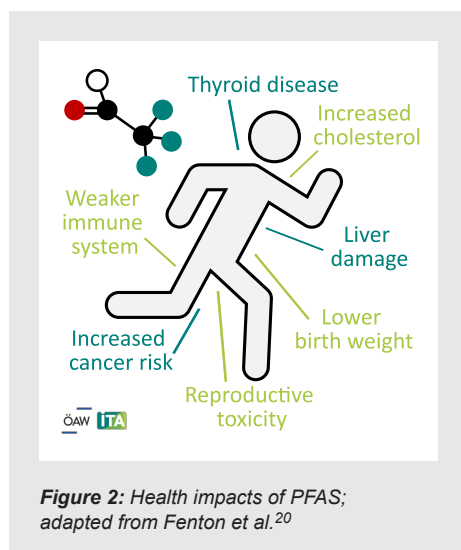
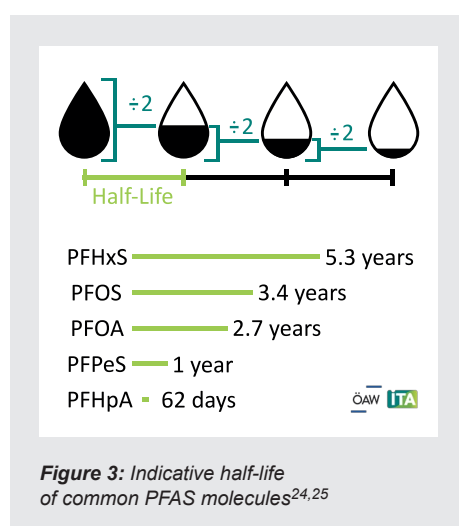
Release into the environment

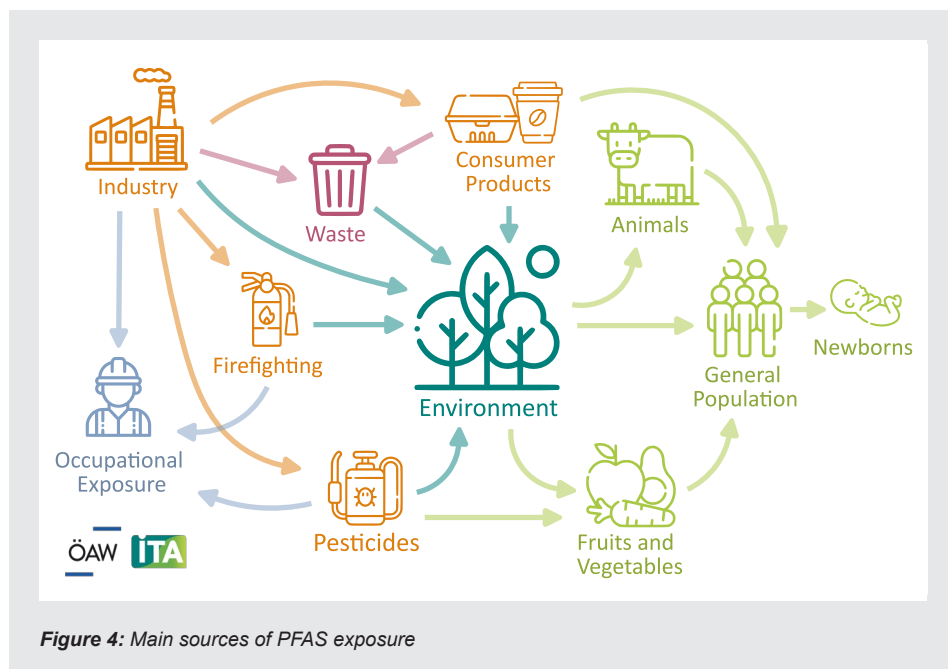
Industrial facilities release PFAS into the environment during the synthesis of these substances and the manufacture of PFAS-containing products.²⁶ The use of PFAS-based firefighting foams is another major source of contamination, particularly around airports, military bases, and firefighting training sites. The *Forever Pollution Project* documents 23,000 known and 21,500 potential polluted sites across Europe, including accidental spills.²⁷

Consumer products containing PFAS are also a significant source of environmental release. For instance, washing waterproof clothing causes emissions into wastewater, the use of certain cleaning products may result in releases to indoor and outdoor air, and PFAS in food packaging can migrate into food and drinks. A product's end of life does not end the life of the PFAS it contains: they remain in solid and liquid waste streams, continue to leach into the environment, and may partially degrade into smaller PFAS compounds.

In agriculture, PFAS are added to certain pesticides to enhance their performance and may also form as degradation products of other chemicals.²⁸ In addition, fertilisers derived from wastewater sludge can contain PFAS transported through sewage systems.²⁹

As a consequence of their widespread use in consumer products and industrial processes, creating multiple release pathways, PFAS accumulate in air, water, and soil, and are now detected worldwide, even in notoriously remote locations such as the Svalbard archipelago, the Southern Ocean, and the summit of Mount Everest.





According to the European Chemicals Agency (ECHA), 4.4 million tonnes of PFAS could be released into the environment over the next 30 years in the absence of further regulatory action.³⁰

Human exposure

Water (both bottled and tap) and food (particularly fish, meat, fruits, and eggs) are the main sources of PFAS exposure for humans and typically account for around 90 % of total intake.³¹ Besides pesticides and water, food-contact materials such as takeaway containers, paper cups, or pizza boxes are a source of PFAS contamination. Additional exposure may occur through dermal contact (e.g., cosmetics and treated textiles) and inhalation of contaminated dust. Exposure begins before birth through placental blood and continues after birth through breastfeeding. According to the European Food Safety Authority (EFSA), the daily dietary intake of four PFAS (PFOA, PFNA, PFHxS, and PFOS) ranges from 0.42 to 41.5 ng/kg body weight per day in adults.³² Intake is twice as high in children and toddlers. EFSA has established a tolerable weekly intake of 4.4 ng/kg body weight for the sum of these four PFAS. Recent findings suggest that current detection methods capture only a fraction of organofluorine compounds released into the environment, potentially resulting in an underestimation of PFAS exposure.³³

Occupational exposure affects workers in chemical manufacturing, firefighting, ski waxing, textiles, and farming.³⁴ These groups may come in

to direct contact with PFAS or PFAS-containing products (e.g., pesticides), and can exhibit blood concentrations 100 to 10,000 times higher than those observed in the general population. Identifying potential exposure routes (e.g., inhalative, oral, or dermal) in the workplace is essential to minimise risk, for example, by ensuring adequate ventilation, using PFAS-free alternatives where possible, enforcing the use of personal protective equipment, and implementing regular health monitoring.

Blood concentrations in the general population vary considerably depending on exposure conditions and can differ by region and over time (see Figure 5 for PFOS). Living near chemical production facilities or in polluted areas is typically associated with higher PFAS levels.

Regulatory landscape

The use, import and manufacture of substances in the EU are regulated by the *Registration, Evaluation, Authorisation and Restriction of Chemicals* (REACH) framework. Specifically, substances identified as *Substances of Very High Concern* (SVHC) may be added to the Authorisation List (Annex XIV of REACH) and become subject to case-by-case authorisation by the European Commission after a specified sunset date. The list of restricted substances (Annex XVII of REACH) sets limitations and conditions for their use on the market. For example, PFAS-based firefighting foams with a total PFAS concentration above 1 mg/L will be banned from October 2030 under Annex XVII.

In addition to REACH, some PFAS fall under the EU's *Classification, Labelling and Packaging* (CLP) regulation, which aims to increase transparency by requiring appropriate packaging and labelling of hazardous substances. PFAS listed under the Stockholm Convention on Persistent Organic Pollutants are also regulated through the EU POPs Regulation.

More broadly, the *Chemical Strategy for Sustainability*, part of the EU Green Deal, aims to reduce the industrial use of PFAS and to promote the development and uptake of safer alternatives. Ultimately, this strategy seeks to phase out all PFAS in the EU, allowing their use only where they are proven essential for society.³⁵ In 2023, five European countries proposed a broad restriction on PFAS within REACH, granting only time-limited derogations when no suitable alternatives are available.³⁰ ECHA announced its support for the proposal in March 2026, and a decision by the European Commission is expected in 2027.

However, PFAS already released into the environment will persist for decades and continue to accumulate. Moreover, virtually every PFAS molecule currently in consumer products will end up in the environment. In addition to reducing future emissions, EU regulators aim to minimise population exposure by limiting environmental releases and setting maximum concentrations of PFAS in water and food.

The *Drinking Water Directive* (DWD)³⁶ introduces limit values for PFAS in drinking water, defining two parameters: (1) the total concentration of measurable PFAS and (2) the concentration of a defined list of 20 PFAS selected due to their adverse health impacts. Member states may

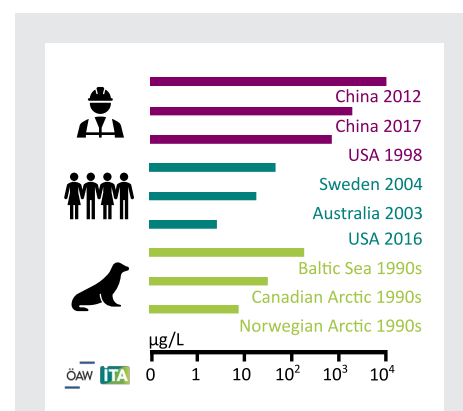


Figure 5: PFOS concentration (phased-out in the 2000s) in the blood of chemical plant workers³⁴, the general population³⁴ and arctic seals¹⁵. The values were selected to reflect the wide range of concentrations.

choose which parameter to monitor. Austria chose to monitor the list of 20 PFAS. Compliance with limit values has been mandatory since January 12th, 2026.

Measurements of Austrian drinking water indicate that in 99 % of cases, PFAS concentrations were below the regulatory limit of 0.1 µg/L (applicable since January 2026), and in 90 % of the cases, they ranged between 0.01 µg/L and 0.1 µg/L.³⁷ However, significant regional disparities exist, and concentrations can be considerably higher in polluted areas.

The *Groundwater Directive* (GWD)³⁸ seeks to protect groundwater quality by preventing or limiting the entry of pollutants. A revision, proposed by the European Commission in 2022⁸ includes regulating the four legacy PFAS (PFOS, PFOA, PFHxS, and PFNA), which are among the most thoroughly studied and are associated with significant health impacts.

Surface waters are regulated under the *Environmental Quality Standards Directive* (EQSD). In its most recent revision, the EQSD establishes limits for the sum of 25 PFAS.

The applicable limit values for PFAS in water are summarised in Table 1.

Based on EFSA's assessment of a tolerable weekly intake, the *Scientific Committee on Health, Environmental and Emerging Risks* recommended a limit value of 4.4 ng/L for PFAS in drinking water.³⁹ Several EU countries have adopted stricter national limits than those set by the DWD (0.50 resp. 0.1 µg/L), including Denmark (2 ng/L), Sweden (4 ng/L), the Netherlands (4.4 ng/L), and Germany (20 ng/L).

The complex regulatory framework governing PFAS concentrations in water reflects the regulators' efforts to keep pace with the rapidly evolving scientific evidence. The European Commission has expressed its intention to further harmonise PFAS regulation in the future.

Commission Regulation 2023/915 (Contaminants Regulation) establishes maximum levels for four legacy PFAS in food. It sets individual limit values for each of the four substances, as well as a cumulative limit for their presence in meat, fish, molluscs, and eggs.⁴⁰ Additional restrictions are set in the legislation on urban wastewater, industrial emissions, toys, packaging and packaging waste.

Impacts on society

In 2018, the Nordic Council of Ministers assessed the annual health costs of PFAS exposure in Europe at between €52 billion and €84 billion.⁴¹ In the United States, estimates for 2018 range from \$5.5 billion to \$62.6 billion.⁴² In a study published in January 2026 the European Commission estimated the health-related costs of PFAS exposure in Europe at €39.5 billion in 2024, attributing about 1,050 statistical deaths to exposure to PFOS, PFOA, PFHxS, and PFNA.⁴³ Projections for 2050 range from €29.5 billion under a business-as-usual scenario to €0.5 billion in the event of a complete ban on production and use.

Including remediation costs for removing PFAS from contaminated water and soil, the European Commission estimates total costs for the period 2024–2050 at between €330 billion (assuming a full ban on PFAS production) and €1.7 trillion (assuming stricter environmental guidelines without further restriction on production).⁴³ The business-as-usual scenario, reflecting current policies, would result in costs of approximately €440 billion. The *Forever Pollution Project* estimates decontamination costs of up to €2 trillion to address legacy PFAS and ongoing emissions, plus an additional €100 billion per year to manage future emissions.²⁷ These high remediation costs reflect the increasing difficulty of maintaining health-based standards for drinking water and food in the absence of comprehensive regulation, as PFAS continue to accumulate in the environment.

Without applying the *Polluter-Pays Principle* to PFAS pollution, citizens will bear the vast majority of related costs. Recent rulings in the Netherlands⁴⁴ and Italy⁴⁵ have set historic precedents by recognising manufacturers' criminal liability for PFAS pollution.

A 2025 report commissioned by the European Parliament⁴⁶ highlights the practical challenges of implementing a full PFAS ban in the EU. Currently, no viable alternatives are available in certain critical sectors, including aerospace and semiconductor manufacturing. Clean technology and renewable energy industries also rely on PFAS, raising concerns that an immediate ban could slow the energy transition while alternatives are still under development. The report therefore recommends time-limited sector-specific derogations to be lifted once suitable alternatives become commercially available.

Research focus

The European Commission currently funds about 50 PFAS-related projects under the *Horizon* framework programmes, for a total investment of approximately €120 million. These initiatives are structured around four main research priorities: (1) detection of emerging PFAS in the environment, (2) the development of effective removal and remediation technologies, (3) the investigation of health impacts, and (4) the development of safer alternatives.

Among major projects, *GENESIS* focuses on developing PFAS-free polymers for the semiconductor industry. *ZeroF* and *BIO-SUSHY* aim to develop PFAS-free coatings for food packaging and textiles. *PFAS everywhere* explores innovative techniques for removing PFAS from human blood, while *FOREVER-WATER* is developing graphene-based water-treatment technologies to eliminate PFAS from wastewater.

The PARC Project brings together 200 partners from 30 countries to develop chemical risk assessment tools, for a total funding of €400 million over 7 years.

Table 1:
EU maximum concentrations of PFAS in water

Regulation	Applies to	Parameter	Value	Entry in force
Drinking water [DWD]	Drinking water	PFAS Total*	0.50 µg/L	12.01.2026
		Sum of 20 PFAS§	0.10 µg/L	12.01.2026
Groundwater [GWD]	Groundwater	Sum of 20 PFAS	0.10 µg/L	Proposal
		Sum of 4 PFAS#	0.0044 µg/L	Proposal
EQSD	Surface water	Sum of 25 PFAS†	0.0044 µg/L	Proposal

* PFAS Total refers to the total concentration of all detectable PFAS in water.

§ Sum of 20 PFAS refers to a list of 20 PFAS molecules selected for their health impacts.

Sum of 4 PFAS refers to the four legacy PFAS [PFOS, PFOA, PFHxS, and PFNA].

† Sum of 25 PFAS refers to the 20 PFAS in the DWD and the GWD, plus the four legacy PFAS and an additional molecule, TFA.

Conclusion

Health impacts associated with the widespread use of PFOS and PFOA, followed by their replacement with equally hazardous, or in some cases more hazardous, chemicals, are now costing European society tens of billions of euros annually. PFAS already accumulated in the environment will persist for decades, generating remediation costs estimated in the hundreds of billions of euros to safeguard food and water quality. At the same time, a generalised PFAS ban would entail substantial costs for the European industry, amounting to tens of billions of euros per year due to lost competitiveness and the investments required to transition to safer alternatives.

A strict phase-out of all PFAS is necessary to prevent further environmental releases, without waiting for full toxicological assessments of the roughly 1,400 individual PFAS molecules in industrial use. Such a process should include sector-specific, time-limited derogations for essential applications where alternatives are particularly difficult to develop or where existing substitutes may pose comparable or greater risks (e.g., clean energy technologies, semiconductors), and be backed by a cost-benefit analysis fully accounting for indirect costs borne by society. Robust emissions-control measures must be implemented to minimise releases throughout the lifecycle, particularly at the end-of-life stage, to limit contamination of wastewater and solid-waste streams. A clearly defined phase-out pathway will reduce regulatory uncertainty and quickly redirect investments towards the development and industrialisation of safer alternatives.

Polluters need to be held accountable for health and remediation costs by applying the Polluter-Pays Principle to PFAS emissions, which will ease the burden that currently lies on citizens and push manufacturers to include societal costs and benefits in their innovation process.

The case of PFAS illustrates the difficulty of regulating new chemicals and advanced materials under high uncertainty about their health and environmental impacts. It underscores the need to proactively integrate health and environmental considerations at the earliest stages of advanced materials development. This would enable the identification of potential negative externalities and allow timely corrective action. For materials for which no safer alternatives currently exist, socio-economic assessments ensure that their use is restricted to applications that deliver clear societal benefits, such as accelerating the energy transition or enabling critical medical technologies, where these benefits outweigh the associated risks. Complementary lifecycle analyses are important to minimise environmental releases.

Early and continuous collaboration between industry and regulators is crucial to help identify priority areas for research and accelerate the development of viable substitutes. Such cooperation enhances regulatory preparedness, strengthens long-term competitiveness and reduces the risks and costs caused by a sudden ban of problematic substances.

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All URLs have been checked on March 19, 2026.
Source for the icons: Freepik, on flaticon.com.

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