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POSTnote

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Regulation and remediation of 'forever' chemicals

Overview

- Per- and poly- fluoroalkyl substances (PFAS) are a group of over 10,000 man-made chemicals, which are widely used in products and industrial processes. PFAS are resistant to degradation due to their chemical properties.
- PFAS are widespread in the environment – they are found in groundwater, rivers, soils, and the atmosphere – and in humans and wildlife.
- Some types of PFAS have been found to be harmful to human and wildlife health, with research showing links to certain cancers, weakened responses to vaccination, and thyroid disease, as well as other impacts. The types and certainty of health impacts vary between different PFAS.
- Remediation of areas or groundwaters with high levels of PFAS contamination requires funding, sustained effort, and cooperation between industry, users, and regulators.
- Alternatives to PFAS are available for many uses in industry, but there are critical exceptions such as medical, industrial, fibre optic and aviation uses for which developing alternatives is challenging, costly, and time intensive.
- There are economic opportunities of research into monitoring and remediation technologies, and innovation in alternatives to PFAS.

Background

Per- and poly- fluoroalkyl substances (PFAS) are a diverse group of over 10,000 synthetic chemicals[1] (Box 1). They are also known as "forever chemicals" due to their persistence in the environment. PFAS products, due their resistance to heat, oil, water, and staining, are extremely versatile and have a wide range of applications including:[2–7]

- Firefighting foams
- Water-resistant treatment of fabrics such as carpets and clothing
- In human and animal medicines, and insecticides, fungicides, and herbicides.
- Non-stick layers for cooking appliances (such as Teflon), and food packaging
- In the electronics industry, such as insulation for electrical wiring
- In the hydrogen industry, during production, transport, and end use
- In the defence industry, such as in munitions

PFAS have come under increasing research and regulatory scrutiny due to their persistence in the environment, accumulation in organisms and biomagnification up the food chain, and risks to human and wildlife health.

Box 1: What are PFAS?

PFAS are a large group of synthetic chemicals that have been widely used since the 1940s. PFAS are characterised by carbon-fluorine bonds, one of the strongest in organic chemistry. Consequently, PFAS can withstand chemical degradation and high temperatures and are sometimes referred to as 'forever chemicals'. Definitions of PFAS vary, either classifying by structure, for example:

- European Chemicals Agency (ECHA) – proposed:[8]
  - "Any substance that contains at least one fully fluorinated methyl (CF_3-) or methylene (-CF_2-) carbon atom (without any H/Cl/Br/I attached to it)" with some exceptions.

Or by specifying a list of relevant substances, for example:

- European Food Safety Authority (EFSA):[9]

0.1 µg/L for the sum of 20 specific PFAS.

Both PFOS and PFOA were banned internationally in 2020 under the Stockholm Convention on Persistent Organic Pollutants (PN 579).

In a precautionary approach, potential for severe consequences is a sufficient criterion for action and regulation, even when facing high uncertainty. Risk-based approaches acknowledge potential for toxicity of the chemical, but reduces risk posed by controlling the human and wildlife exposure to the chemical.

– 4 PFAS prioritised for monitoring – including perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA) – and 24 additional substances to be monitored 'if possible' or 'considered' for monitoring.

PFAS production has shifted from longer chain molecules (C8s, with eight carbon atoms) to shorter chain molecules (C4s, with four carbon atoms), with reports of decreased ability to bioaccumulate and lowered toxicity,[1] although there is limited evidence for this. Shorter chain PFAS have been shown to be more persistent, but have been found to be eliminated more rapidly than longer chain PFAS in many organisms[10], leading to lower bioaccumulation.[11]

PFAS distribution and exposure

PFAS in the environment can be transported by water,[12] leach out of or bind to solids,[13,14] and be carried in the air.[15] The fate of PFAS depends on their characteristics and environment. The variable behaviour of PFAS depending on their environment is a current research gap: the mobility of PFAS in the environment, their tendency to bind to protein and other substances, and their ability to evaporate all vary with pH, temperature, and salinity.[16]

Lighter, shorter-chain PFAS tend to be highly mobile, dispersing quickly through water and solids, and less likely to bind to soils; heavier longer-chain PFAS tend to be less mobile, and are more likely to bind to soils and sediment.[17]

The sources and transport of PFAS in the environment are shown in Figure 1. The concentration of PFAS in the environment varies strongly between area. There are strong 'hotspots' of contamination (with notable examples in Table 1), generally from industrial or military sources such as:[18–20]

- Firefighting training with PFAS-containing firefighting foams contaminating training sites. These leach PFAS into the surrounding area through rainwater run-off.
- Improper containment or lining of landfills, especially historical landfills.
- Emissions from factories working with PFAS, either used for making products or used for components of products.

Patterns of contamination

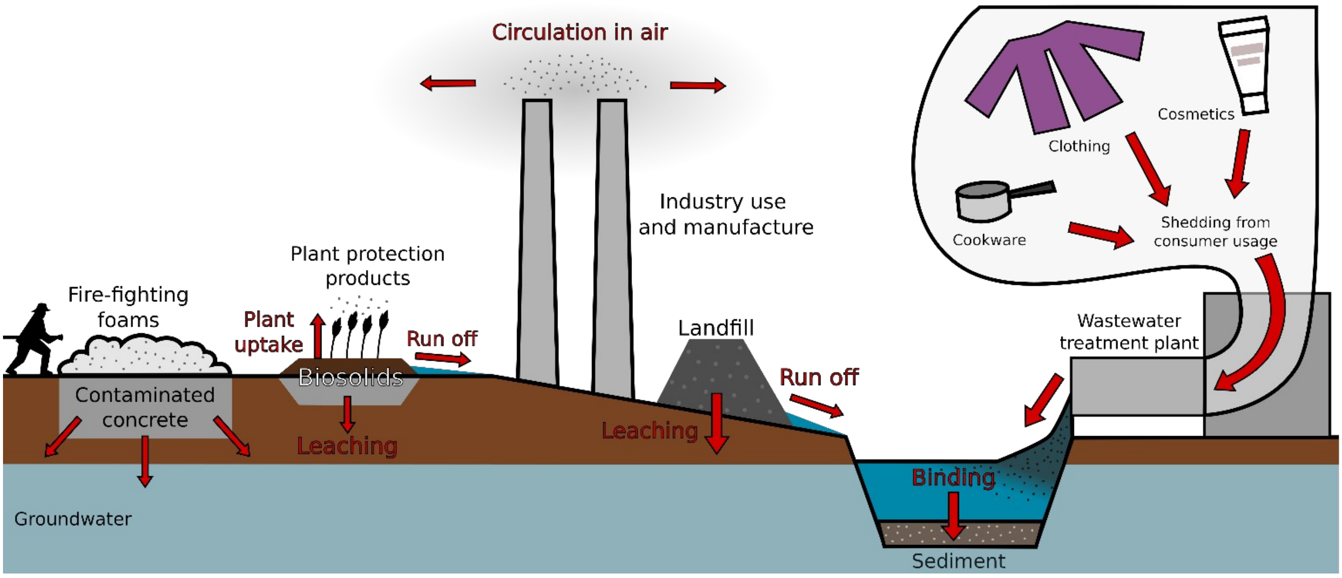
PFAS pollution is globally widespread. A global study of 45,000 water samples – chosen to avoid sources of contamination – found PFAS present in surface water and groundwater worldwide.[21] 31% of groundwater samples had concentrations of PFOA (a banned type of PFAS, see Box 1) above levels deemed safe by the US Environmental Protection Agency.[21]

Low background levels of PFAS are found almost everywhere, due to diffusion of PFAS from hotspots (see below), as well as consumer usage of PFAS containing products, such as clothing and cosmetics.[22,23]

Contamination across the UK is spatially complex, with different patterns of contamination associated with each source depending on the geography of the local area and type of PFAS contamination. There is no one-size-fits-all approach to designating areas of concern for PFAS contamination around sites, and identifying these areas would require on-site sampling.

Monitoring by the Environmental Agency (EA) has found detectable levels of PFOS (Box 1) at over 99% of surface water sites sampled, detectable levels of PFOA at over 99% of freshwater sites and over 96% of estuarine and coastal sites sampled.[24]

Figure 1 PFAS sources and transport



PFAS hotspots

PFAS found at hotspots can be traced to industrial activity in production or usage of PFAS in manufacturing processes, or the usage of PFAS-containing fire-fighting foams at both domestic and military airfields.[25] Table 1 lists some notable examples of PFAS contamination hotspots, along with impacts and actions associated with the contamination.

Table 1

Hotspot site	Contamination type	Outcomes
Bentham, North Yorkshire, UK	PFAS from production and testing of firefighting foams at Angus International Safety Group (Angus Fire) site.[26] PFOS concentrations in groundwater (2,600 nano gram per litre in 2010, and 10,700 ng/L in 2018)[27] at levels 4,000 to 16,000 times the environmental quality standard[a]	Cleaner Bentham community group organising legal action against Angus Fire. No results of blood screening available currently, though testing is planned by Cleaner Bentham.[30] A survey of publicly available health data shows that Bentham has an increased rate of cancer compared to

	(EQS).[29] There is no EQS for total PFAS or PFOA, though the levels found (47,200 ng/L in 2010, and 63,400 ng/L in 2018 for total PFAS; 1,300 ng/L in 2010, and 2,500 ng/L in 2018 for PFOA)[27] were of high concern to PFAS researchers.	surrounding areas, though a cause has not been isolated.[31]
Island of Jersey, British Isles	Contamination from PFAS-containing fire-fighting foams used at Jersey Airport for training.[32] Blood testing found 30%-70% of residents had levels of PFAS higher than 95% of US population.[33]	Bloodletting recommended as a potential treatment for residents with high levels of PFAS.[32] £2.6 million from 3M used for remediation, and £500,000 from Jersey Airport used to connect mains water supplies to areas using private boreholes.[33]
Parkersburg, West Virginia, USA	PFOA contamination from Dupont's Washington Works plant.[34] PFOA levels in blood serum of nearby residents up to 500% higher than the general US population.[35,36] A groundwater site measurement in Parkersburg in 2019 by US geological survey found a PFOA concentration of 1,540 ng/L.[37]	US Environmental Protection Agency settled lawsuit against DuPont for US$16.5 million in 2005.[38] DuPont settled 3,550 personal injury claims related to the Parkersburg contamination for US$671 million in 2017.[39]
Australian military sites: Royal Australian Air Force (RAAF) Base Tindal, Oakey Army Aviation Centre, RAAF Base Williamtown, Australia	PFAS from the use of firefighting foams at military sites - there are no PFAS manufacturing facilities in Australia.[40] Elevated PFOS measured in current residents of the sites, up to three times the general US population levels.[41,42]	Treatment or removal of over 160,000 tonnes of contaminated soil AUD$807 million invested in management, remediation and research.[43] Communities in affected sites settled 3 lawsuits against Australian government for AUD$212.5 million citing property value loss, injury, and distress.[44]

PFAS exposure

Human exposure can occur through:

[a] Both PFOS and PFOA were banned internationally in 2020 under the Stockholm Convention on Persistent Organic Pollutants (PN 579).

- Ingestion of PFAS through water.
  - Drinking water sources can be contaminated with PFAS.[45] There are no records of UK public drinking water exceeding guideline limits for PFAS, though this has limited testing.[46] Private water abstraction from groundwater can pose risks, as some sources may be highly contaminated with PFAS.[47]
- Ingestion of PFAS through diet.
  - PFAS in soil and water is accumulated by plants and animals in the local environment, through their exposure.[48]
  - Sewage sludge, or biosolids, are regularly used as fertilisers in the UK.[49] There is currently no monitoring or regulation for the concentration of PFAS in sewage sludge or of soils, and there is no treatment to remove PFAS present in sewage sludge.[50–54] Studies suggest crop and livestock forage plants can uptake PFAS from soils.[48,55–64]
  - In animals PFAS can be further concentrated by movement of PFAS up the food chain. Animal products in general, but particularly liver and eggs have been identified as foods containing higher levels of PFAS.[65–73] Eating fish, poultry, cheese, and red meat at least once per week has been associated with higher levels of several types of PFAS.[6,74–78]
  - PFAS is also found in some food contact materials, [79–82] though the migration from packaging to food and human uptake of the PFAS is variable.[83–85]
  - The contribution to human intake of PFAS from foods themselves compared to PFAS-containing food contact materials is unknown.[86–88]
- Breathing in PFAS from the air.
  - Workers who are occupationally exposed to PFAS may be working in areas where PFAS in the air poses a risk to them.[89,90]
  - PFAS emissions from landfills into the air may pose risks to local residents.[90–92]
- Dermal contact with PFAS.
  - PFAS in contact with the skin can be absorbed into the human body.[93–95] Products such as clothing with anti-stain PFAS coatings and fitness watches with PFAS-coated straps may therefore increase PFAS concentrations in humans.[22,23,96,97] However, research on this area is limited.

The contribution from each form of exposure will vary from person to person.[6] However, diet has been identified as the dominant contributor to PFAS exposure for most humans, other than those occupationally exposed.[87]

PFAS exposure and impact challenges

PFAS monitoring

Investigations in the UK monitoring PFAS levels in humans are limited. One study using data from the Human Biomonitoring for Europe project found PFAS in every blood sample taken, at PFAS concentrations for which "health effects can no longer be ruled out" in up to a quarter of the samples.[98]

A US study found PFAS compounds present in over 98% of human blood samples.[99] PFAS substances found in both studies include PFOS and PFOA, which have largely been phased out due to bans with limited exemptions.

PFAS contamination is widespread in livestock. A study on farm animals in Japan in 2008, including chickens, cattle, goats, horses, and pigs, found PFOS in all samples taken. PFAS in livestock has been found to gather preferentially in the liver, followed by eggs and muscle.[100]

PFAS contamination in water is routinely monitored by the EA at over 500 sites targeting 48 different types of PFAS around the UK (Box 2).[7,101] The total length of watercourses across the UK is around 200,000 km, meaning that there is roughly one site for every 400 km of waterway.[102] Approximately 100 individual PFAS are registered as being supplied to the UK market in amounts greater than 1 tonne per year.[7,103] Therefore, researchers raise concerns that monitoring a limited subset of PFAS may lead to high contamination from unmonitored PFAS being missed.[3]

The EA currently do not routinely monitor soils or PFAS in air. There has been some research which notes that the contribution of airborne PFAS to individual PFAS exposure is a minor pathway,[104] but may be a source of work-related PFAS exposure.[91] Evidence is limited, and could be affected by individual lifestyle choice, such as the use of spray-on products containing PFAS surfactants, compared to community-scale air quality.[105]

Biological sentinel monitoring[a] of PFOA and PFOS in freshwater and marine fish has been previously carried out by the EA.[7] Otters have also been used by both Cardiff University[106] and the EA; comparing measurements of PFAS in otters to those in fish gives an indication of how PFAS is moving through the food chain.[7]

Box 2: Monitoring types

When monitoring substances in the environment, there are several options in choosing the method used. The first is the type of sampling:

- **One-off 'grab samples'** of the medium (for example water or sediment), for measuring the instantaneous concentration of contaminants in the medium.[107,108]

[a] Environmental quality standards are guidelines defining acceptable levels of pollutants in water, soil, and other media. They are designed to prevent adverse health and environment impacts.[28]

- **Passive sampler devices** gradually absorb contaminants from the medium, and so can be used to calculate the average chemical concentration over the time that the device is in place.[108]

The method used to determine the concentration of contaminants in the sample is also important. This can be either:

- **Targeted**: measuring specific substances individually. This means that the concentration of individual PFAS substances, for example PFOS or PFOA, can be found. However, PFAS that are not targeted will not be measured at all. For example, a sample could be highly contaminated with PFOS but determined to be relatively 'clean' if only PFOA concentrations were measured.[3,109]
- **Non-targeted**: measuring groups of substances as one. This means that the concentration of all substances in a group (organic fluorinated substances in the case of PFAS) are measured. This means that substances will not be 'missed out' as they could be in the targeted method. However, this approach will not indicate which specific substances are found in the highest concentration, and the concentration measured may also be increased by other non-PFAS substances present in some cases.[3,110,111]

There are concerns from some academics that regulation will be hampered by a lack of chemical reference standards for many types of PFAS, making it harder to perform risk assessments and enforce regulations of individual PFAS through targeting monitoring.[3,112,113]

Several water companies have shown interest in projects aiming to combine multiple monitoring PFAS methods into single devices.[3]

PFAS health impacts

Wildlife health impacts

Research studies demonstrate impacts on liver, immune, and developmental processes in laboratory animals from exposure to PFAS.[114] Table 2 lists identified responses to PFAS in laboratory animals.

Table 2

Animal	PFAS type	Response type
Monkeys	PFOS	Liver toxicity, weight loss, hormonal changes
Mice	PFOA	Liver, reproductive, and developmental toxicity
Rats	PFOA and PFOS	Carcinogenic (increased testicular, liver, and pancreas tumours), reproductive and developmental toxicity

Rabbits	Mixture of PFAS	Reproductive and developmental toxicity
Otters	PFOA and PFOS	Immune system weakening
Polar bears	Mixture of PFAS	Nervous system effects, hormonal changes
Seals	Mixture of PFAS	Hormonal changes
Birds	Mixture of PFAS	Eggshell thinning, reduced hatching success, hormonal changes
Fish	Mixture of PFAS	Behavioural changes, immune system changes
Dolphins	PFOS	Immune system changes
Frogs	PFOA and PFOS	Decreased liver function
Turtles	Mixture of PFAS	Reduced hatching success, immune system changes
Alligators	Mixture of PFAS	Immune system changes and skin lesions

Source: Summarised information from [100,115].

There are few studies on health impacts of PFAS on animals outside the laboratory. Variations in exposure to PFAS between species, due to differences in elimination rates, exposure routes, and environmental contamination levels, add complexity to identifying health impacts.[116,117]

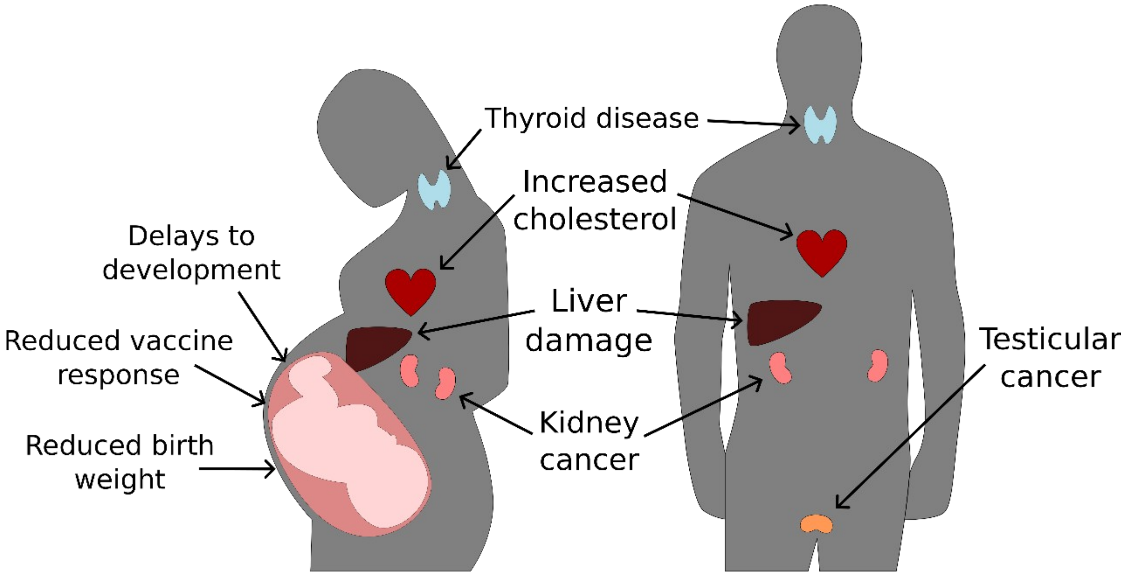
Human health impacts

Human health effects are summarised in Figure 2. There is considerable disagreement in literature on the magnitude of impacts from PFAS exposure, or the required exposure level at which adverse health effects occur.[118]

Identified responses to PFAS cited in policy and regulation documentation include: suppressing of immune responses to vaccines in children, increased cholesterol levels, decreased birth weights, and poorer neurodevelopment.[a,119]

[a] Monitoring using living organisms, such as animals or plants, to detect and gauge hazards in the environment.

Figure 2 Human health impacts of PFAS



Source: [120–126]

Uncertainties remain about the health effects of PFAS.[127,128] Further epidemiological studies of PFAS-affected areas could result in changes to regulatory PFAS environmental thresholds.

Interactions with other pollutants

PFAS are often found in pollutant mixtures in the environment. Components of these mixtures may include:

- Micro- and nanoplastics (PN 724):
  - Plastic fragments smaller than 5 mm and 1 μm respectively.
- Other persistent organic pollutants (POPs) (PN 579)
  - A wide variety of degradation-resistant, toxic substances, including banned substances such as polychlorinated biphenyls (PCBs), which were widely used in manufacturing, and dichlorodiphenyltrichloroethane (DDT), which was widely used as a pesticide.

Ecotoxicological researchers have noted concerns about mixtures of polluting chemicals; responses to these mixtures may be stronger than the added sum of all responses to the individual substances. This could be due to interacting health effects, or mechanisms which can increase or decrease the effective dose of substances.[129–131,a]

However, research in the area has only recently started to develop, and disagreement in literature is common.[133] The EA published recommendations addressing risks of chemical mixtures, which briefly mentioned PFAS, in 2022.[134]

[a] Highly purified samples of compounds with a known concentration and purity, acting as benchmarks for measurements performed by laboratories.

Opportunities in PFAS

Some companies have reported complications from EU PFAS manufacturing facilities ceasing production in response to pending EU regulations on PFAS (see below).[135,136] Continued use of PFAS in areas such as medicine, aircrafts, and military may become economically unviable despite EU derogations for critical uses.

There has been increased research and development of lower risk substitute materials that can replicate the useful properties of PFAS, such as thermal and oil resistances.[137,138] However, 'regrettable substitutions' could occur where the substitute material are later found to pose risks.[139,140]

Only limited numbers of PFAS alternative materials have been shown to be effective replacements, and commercial scaling up of their production may be challenging.[137] In addition, replacement and removal of PFAS in products requires knowledge of PFAS presence and usage. However, there is limited ability to track and understand where PFAS is introduced in supply chains, due to differing international standards for labelling materials and low transparency in supply chains.[141,142]

Some PFAS are used in products for only one of their properties, such as water repellence, and can be replaced with existing alternatives. However, replacing PFAS in products requires full understanding of product uses of the product, and may not be possible for critical uses.[136,143]

There are several UK consultancies and manufacturers helping companies transition from the usage of PFAS products to alternatives,[144–146] and the European transition provides an economic opportunity to these businesses. UK universities are world leaders in materials research such as developing PFAS alternatives.[147]

Remediation strategies

Several sites of contamination are 'legacy' sites, where PFAS emissions have been halted, however PFAS is still found at high levels in the surrounding environment.[148,149] Often, this is due to stored PFAS leaching out from contaminated materials, such as concrete or soil, so that the site is still a source of PFAS emissions.[150,151] In these cases, remediation strategies are often used to destroy or remove remaining PFAS. Remediation strategies have also been proposed for use in removing PFAS found at a low level in constant circulation.[152]

However, PFAS remediation is expensive with currently available technology. For example, in Doetinchem, the Netherlands, the removal of 34 g of PFAS from groundwater cost over €1 million.[153,154] Current estimates of PFAS remediation costs are highly uncertain, though the cost of remediation across the EU has been estimated at €2 trillion over 20 years by the Forever Pollution Project, a journalism investigation launched in 2022 to report on PFAS pollution in Europe.[155]

In the UK, the EA are working to provide a more detailed summary of the current PFAS remediation methods available. Current technologies applicable to the remediation of PFAS contamination are noted in Table 4. However, many of the approaches are yet to be proven at an appropriate scale.[156,157]

Currently, thermal destruction using incinerators is one of few methods known to remain effective across the whole range of PFAS, though is extremely energy-intensive, and produces hazardous byproducts such as free radicals.[a,158] Disposal of waste through thermal incineration is, along with disposal in landfill, at the bottom of the waste management hierarchy (CBP 10229).

Many other methods are only effective for subsets of PFAS, do not destroy or break down PFAS, or are not yet applicable for large areas of remediation.[156,159,160] For emerging technologies, additional research is needed before they are feasible, cost-effective and applicable for remediation in the UK.[156]

Table 3

Remediation technique	Summary	Advantages	Disadvantages
Adsorption (attraction of dissolved substances to a material, resulting in a film of the substance on the adsorbent material)	PFAS contamination adheres to adsorbent material in water over time. Includes natural adsorbents and nanomaterials.	Efficient, effective, simple to operate, no/low emissions.	Reliant on characteristics of environment including pH, concentration of pollutant, properties of pollutant, and temperature. Treatment or disposal of adsorbent material necessary.
Reverse osmosis and nanofiltration	Common water purification process using semi-permeable membranes or filters.	Effective across chain lengths and chemical structures.	Maintenance of membrane health necessary, especially with groundwater applications.
Plasma technology	Strong plasma pulses in water cause PFAS to be broken down.	Potential to greatly increase degradation efficiency.	Full scale application not yet possible due to high cost.
Foam fractionation	Air or gases are forced into the medium, forming a foam layer where PFAS gathers in high concentration.	Effective across wide range of contaminants.	Not effective in reducing contamination to lower regulatory limits. Creates foam waste, requiring further treatment or management.
Biodegradation	Enzymes and bacteria are used to ingest and	No/low emissions.	Requires extended research, and

[a] Neurodevelopment refers to how the brain's nervous system develops and organises itself, affecting an individual's ability in processes such as learning, memory, and social skills.

	transform PFAS.		processing usually extremely slow even under lab conditions.
Incineration	High temperatures in incinerators (>850°C) are able to break down PFAS.	Effective across wide range of PFAS, can be scaled to appropriate levels.	High operational costs from high energy use, transportation of material, waste management. Sustainability concerns over transport emissions, energy usage, and harmful emissions during incineration.
Sonolysis	High frequency sound waves are generated, creating bubbles in water, which collapse and release heat energy, causing temperatures up to 4700°C within the bubbles. Pollutants in the solution are destroyed with high temperatures.	Operationally simple and efficient, with limited environmental concerns.	Full scale application not yet possible due to high cost.
Electrochemical oxidation	Strong electrical currents are used to break the carbon-fluoride bond in PFAS.	Effective across wide range of pollutants.	Less effective for short-chain PFAS. Maintenance of equipment required. Generates toxic byproducts.

Source: Summarised information from [156,161–164]

Remediation can be performed *in-situ* or *ex-situ*. For *in-situ* remediation, the medium is treated at the site of contamination, such as water through activated carbon filters.[165] For *ex-situ* remediation, the medium is removed and transported to external remediation facilities for treatment or disposal.[166]

In-situ methods have lower transport costs and less logistical complexity, but in some cases *ex-situ* treatment of contaminated media is necessary to prevent the spread of further PFAS contamination.[161,167]

Several countries have begun widespread remediation efforts for PFAS contamination:

- The Netherlands:

  - Remediation at 28 sites, including previous sites of textile factories, firefighting training areas, and previous airbase sites. By January 2025, costs associated with ongoing remediation had reached €70 million.[168,169]

- Australia:

  - The Australian Defence Force (ADF) has identified 28 priority sites for remediation, and removed 160,000 tonnes of contaminated soil, along with other measures for reducing PFAS exposure. The ADF has invested AUD$807 million in remediation and prevention of PFAS pollution. Information sessions have been organised to update communities on ongoing action and risks.[43,170]

- Belgium:

  - 3M, a PFAS production company, signed a deal with the Flemish government to pay €580 million for remediation and research, but total costs for remediation are expected to be higher. Remediation of the main site of contamination will involve removal of roughly 441,000 tonnes of soil.[171,172]

Many less energy-intensive remediation methods, such as bioremediation, remove but do not destroy the contaminating PFAS, producing PFAS waste to be stored or destroyed.[156,162] However, this may provide an opportunity to recycle other chemicals removed during the treatment, such as phosphate.[a]

Hybrid technologies combining multiple approaches to remediation listed in Table 4 have been found to perform better than single approaches,[156,174] and hybrid technologies combining filtering membranes with other techniques are most common.[156]

Full remediation of PFAS contaminated regions will require bespoke approaches to each site.[175,176] The PFAS type will depend on the source of contamination, which along with the local geography, will impact the contamination distribution.[25,177] The level of exposure risk – such as proximity to drinking water sources or farmland – will determine required remediation speed.[178]

Innovation in remediation technologies may be useful in reducing PFAS levels across the UK and rest of the world. There are several groups in the UK developing new remediation technologies and improving efficiency in existing remediation techniques.[88,157,179–185]

Current regulation of PFAS

The EU's Registration, Evaluation, Authorisation and Restriction of Chemicals (EU REACH) regulation was passed in 2007 and established the European Chemicals Agency (ECHA). EU REACH aims to track the production and use of chemicals, and their impacts on human health and the environment, while ECHA manages the scientific and administrative work necessary to implement regulation. Registration of manufactured or imported chemicals is required, and if the chemical presents a

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[a] For example, if a microplastic fragment that PFAS were bound to were ingested, the resulting uptake of PFAS may be higher or lower than if the same amount of PFAS were ingested without being bound to plastic.[132]

potential risk to human or environmental health, further investigation on the chemical is carried out. However, this evaluation process is time-intensive,[186] and often important safety information is not given upon registration.[187–189] UK REACH regulation "aims to replicate EU REACH as closely as possible" (CBP-8403).[190]

When regulating PFAS using the EU and UK REACH method, individual substances are banned.[191] However, there are concerns from NGOs and academics that manufacturers can make minor changes to the composition, so the chemical is technically different.[3,192] This new substance would not be prohibited, despite exhibiting the same behaviour and posing the same risks. This difficulty could be addressed with a ban of PFAS as a class, but this may stifle innovation in mitigating risks and increase the regulatory work needed in applying derogations.

PFAS limits for drinking water

Legal thresholds and guidelines for concentration of PFOA and PFOS in drinking water differ between countries, as shown in Table 3. Several countries, for example Australia, the US, and Japan, rely on the same key studies, but PFAS concentration limits differ by orders of magnitude, depending on approaches to risk.[193]

For some countries, more complex regulations involving maximum total PFAS levels are also applied.[194] The regulation of PFAS limits in drinking water is subject to continuous change, due to changes of the common PFAS used by industry and updates to scientific understanding of the risks of exposure to PFAS.[195,196]

As shown in Table 3, recent national regulations have been more stringent, driving necessary improvement in monitoring techniques to lower detection limits.[197,198]

Table 4

Country	PFOS limit (µg/L)	PFOA limit (µg/L)	Year
Sweden[199]	0.09	-	2014
Denmark[200,201]	0.1	0.3	2015
US[202,203]	0.07	0.07	2016
Germany	0.1	0.1	2016
Australia[202,203]	0.07	0.7	2017
Canada[200,201]	0.6	0.2	2018
Japan[202,203]	0.05	0.05	2020
US (updated)[204,205]	2×10^{-5}	4×10^{-6}	2021
UK[206]	0.1[a]	0.1[g]	2021
Denmark[207]	0.002[b]	0.002[h]	2022

[a] A free radical is a molecule that contains at least one unpaired valence electron. Chemical molecules are more stable when their electrons are paired with other electrons, so free radicals are often unstable and chemically reactive.

[b] Reserves of phosphates are predicted to be exhausted within 100-250 years,[173] leading to interest in phosphate recycling (PN710 and PN477).

France[193]	0.1[c]	0.1[i]	2023

Source: World Health Organisation Guidelines for Drinking-water Quality, Appendix Table A.1[208]

Differing regulatory approaches

There is active dispute between industry, regulation, and NGOs on the desired approach to PFAS regulation.[3,136,209–211] Approaches to regulation of chemicals in academic literature are either precautionary or risk-based.[d] Both the UK and EU, legal frameworks for PFAS use a precautionary approach (PN 590).[212]

A proposal for a wider restriction on the manufacture, selling, and usage of PFAS as a class of chemicals was submitted by Germany, Denmark, the Netherlands, and Sweden in 2023.[8] This proposal is currently being evaluated by the European Chemicals Agency's (ECHA) scientific committees.[119] A key barrier to the implementation of this restriction is differing stakeholder opinions on what should be included in the PFAS class (Box 1).

ECHA's scientific committees supported a restriction on PFAS use in firefighting foams in 2023,[213] though the restriction has not yet been implemented. EFSA published recommendations that include the monitoring of required and suggested individual PFAS.[214] No specific legal limits are given, although levels above which causes of contamination should be investigated are given. These limits differ between PFAS type, food type, and consumers.

Recent developments

The Danish Government approved a ban on PFAS in food packaging,[215] which began in 2020, as well as a ban of PFAS in clothing,[216] which will come into effect in July 2026. Denmark has also allocated €54 million for a national action plan to prevent and remediate PFAS pollution.[217]

In February 2025, the French Government approved a ban on the manufacture and sale of most PFAS products, which will come into place in stages between 2026 and 2030.[218] Exceptions to this include protective equipment and kitchenware – notable as diet is the main source of PFAS exposure for most people.[4,5,87,88] Kitchenware was originally included in the ban but removed after lobbying from industry.[219] Levies for mass of PFAS emitted by industries has also been agreed, although implementation approaches have not been clarified.[218]

In the UK, the marketing and use of PFAS-containing products may be impacted by the Product Regulation and Metrology Bill, which is currently under discussion.[220]

Some of the key considerations for regulation raised by contributors are summarised in Table 5.

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[c] No statutory standard for PFAS in drinking water in the UK, though 0.1 µg/L for the sum of 48 specific PFAS is provided by the DWI as a guidance limit.

[d] 0.002 µg/L for the sum of 4 specific PFAS.

PFAS concerns

The topic of PFAS contamination has undergone increasing media attention.[27,221–223] Increasing public awareness may reduce individual exposure to PFAS through lifestyle choices.[224,225]

Several charities, NGOs, and other bodies have concerns around PFAS contamination. Calls for action from these organisations include:[209,210,226]

- Remediation at hotspots.
- Implementation of legal thresholds for PFAS contamination of drinking water, as only guidelines for PFAS levels currently exist.
- A complete ban on PFAS products, with timelines in place for implementing alternatives for critical uses, for example in aircraft or medical usage.
- Restructure of approaches to regulating the manufacture and usage of new chemicals, due to repeating cycles of chemicals in wide usage being later identified as substances of concern.

Table 5

Policy consideration	Explanation
PFAS definition	Regulating PFAS requires a definition of PFAS, which is an area of disagreement between stakeholders in industry, academia, and NGOs.[3,136,209–211] Reasoning for the chosen definition is likely to be critical for whether this can be resolved.
Monitoring system	Currently only water and some wildlife are routinely tested for PFAS,[7] but food is the main exposure pathway.[74,75] Levels of PFAS in human blood serum has been identified as an indicator of public exposure to PFAS in contaminated areas for international case studies,[6,115] but is not routinely undertaken in the UK.
Approach to regulation	Chemical regulation requires either a risk-based or precautionary approach, which one is most appropriate remains disputed by NGOs, academics, and industry.
Cost effective remediation approaches	Estimates of the costs of remediating hotspots in the UK vary,[178,227] but widespread remediation of PFAS would likely require new more cost-effective approaches.
Critical use derogations	Several industries have expressed concern over the difficulty in substituting PFAS in critical use cases.[136,137] These difficulties relate to lacking technology in PFAS alternatives, high costs of current PFAS alternatives, and lacking supply chain transparency.

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