

## Forever chemicals, forever problems

### The story of PFAS

**Ellie Tulk**

*This article explores the 'forever chemicals' found in everyday products, and the hidden risks they pose to health and the environment*

#### Exam links

- environmental chemistry
- functional groups
- polymers
- structure and bonding

Over 90 years ago, the first per- and polyfluoroalkyl substance (PFAS) was synthesised. Although carbon–fluorine bonds had been created before, this was the first instance of a compound containing a fully fluorinated methylene group ( $-\text{CF}_2-$ ) or methyl group ( $-\text{CF}_3$ ). The presence of these fully fluorinated carbon groups gives PFAS chemicals unique properties, leading to their use in products such as non-stick cookware, fire-fighting foams, food packaging, stain-resistant fabrics and carpets, tents, and even sportswear. These applications stem largely from their **hydrophobic** and **lipophobic** nature, which allows them to repel both water and oils, as well as their typically non-flammable character.

### A growing global concern

While PFAS chemicals initially appeared to be versatile and well-suited for many applications, concerns about their use have existed since the 1950s, gaining increasing attention as more research has emerged. The same strong carbon–fluorine bonds that give PFAS their functionality also makes them extremely persistent in the environment, earning them the nickname 'forever chemicals'.

As of 2024, it is estimated that over 97% of Americans have detectable PFAS levels in their bloodstream, and these substances can even cross the placenta to reach unborn children. This is particularly alarming given that, out of an estimated 10,000 different PFAS compounds, only a few – perfluorooctane sulfonic acid (PFOS), perfluorooctanoic acid (PFOA), and their salts – are currently banned under the UK's Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation. This highlights not only the scale of the PFAS problem, but also how little is known about the specific chemicals still being used as additives in everyday products.

## What makes PFAS so persistent?

The carbon–fluorine bond, which defines PFAS and gives them their unique properties, is one of the strongest single bonds in organic chemistry, with a bond dissociation energy (BDE) of about 488 kJ mol<sup>-1</sup>. The BDE is the energy required to break one mole ( $6.02 \times 10^{23}$  bonds) of gaseous molecules into radicals.

The C–F bond strength is exceptionally high for two main reasons:

- **Electronegativity difference** – fluorine is the most **electronegative** element, so the shared electrons in the bond are pulled closer to the fluorine atom. This makes fluorine partially negative ( $\delta^-$ ) and carbon partially positive ( $\delta^+$ ), and the attraction between these opposite charges further strengthens the bond.
- **Small atomic radius of fluorine** – being the smallest halogen, fluorine can get very close to the carbon atom. This short bond length increases the electrostatic attraction between nuclei and bonding electrons, with minimal electron shielding.

In addition, the stable electronic configuration of fluorine helps shield the carbon from reacting with other species, making the bond resistant even to highly reactive chemicals. As a result, PFAS are extremely persistent in living organisms and the environment.

Naturally occurring C–F bonds are rare – only a few fluorocarbons are known in nature, many as toxins in poisonous plants. Because of this, very few microbes have evolved enzymes capable of breaking C–F bonds. In PFAS, the large number of C–F bonds and their shielding effect on the carbon backbone make microbial breakdown even more difficult.

## Decades of knowledge, decades of harm

Evidence of PFAS accumulation in the human body has existed since the 1950s. By the 1960s, two major producers were conducting animal studies that confirmed serious health risks. In the 1980s, both companies detected elevated cancer rates among their own employees and linked them to PFAS exposure.

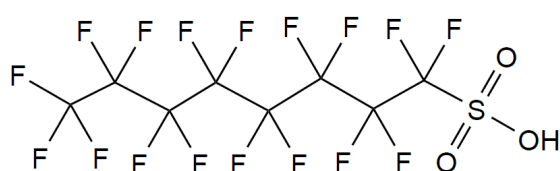
While research into individual PFAS compounds is ongoing, the chemical class as a whole has been shown to cause:

- developmental delays in children, low birth weights, accelerated puberty, bone variations and behavioural changes
- impaired immune function, including reduced antibody responses to vaccines
- endocrine disruption, leading to reproductive issues and thyroid disease
- certain cancers, including kidney, breast and prostate
- elevated cholesterol levels and, more recently, links to childhood obesity
- liver enzyme alterations and organ damage.

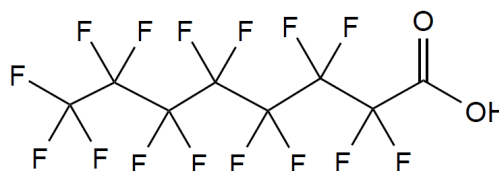
This list continues to grow, as new PFAS chemicals – each with the potential to cause different side effects – are still being synthesised. The largest fine to date for PFAS contamination, approximately US\$10 billion, was issued to 3M for contaminating multiple water supplies in the USA.

## The shifting face of PFAS

PFOS and PFOA share a similar structure (Figure 1), each with an eight-carbon backbone – the origin of their nickname 'C-8'. Every carbon bonding site is occupied by fluorine atoms, except at one terminal carbon, where a functional group is attached: a sulfonic acid group in PFOS and a carboxylic acid group in PFOA.



PFOS  
(perfluorooctanesulfonic acid)

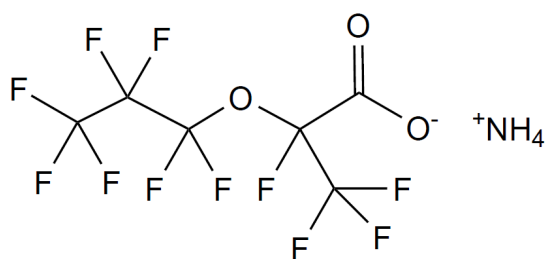


PFOA  
(perfluorooctanoic acid)

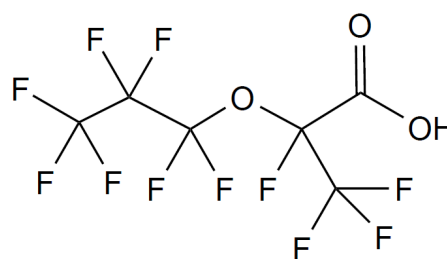
**Figure 1** The structures of PFOS ( $C_8HF_{17}O_3S$ ) and PFOA ( $C_8HF_{15}O_2$ ). They have identical C-8 fluorinated backbones, but different terminal functional groups

PFOS was the first PFAS chemical to face regulation. Although not completely banned worldwide, its use in the UK and European Union (EU) was prohibited in 2009 following its inclusion in the Stockholm Convention on Persistent Organic Pollutants (POPs). PFOA, initially used as a replacement for PFOS, was later added to the Convention in 2019. Research has since revealed that these chemicals are even more toxic when present together.

In response to such restrictions, new PFAS compounds have been developed to fill the gap in the market. One of the most infamous is GenX, also known as FRD-902, a PFAS chemical used in the production of fluoropolymers. This ammonium carboxylate salt comprises six carbons and contains an ether (Figure 2). In the presence of water, GenX can be converted into a carboxylic acid shown to be potentially more harmful than PFOA – yet it is not regulated anywhere in the world.



FRD-902



HFPO-DA

**Figure 2** The ammonium salt FRD-902 has the trade name GenX. When exposed to water, it can be converted into hexafluoropropylene oxide dimer acid (HFPO-DA), a perfluoroalkyl ether carboxylic acid that is potentially more toxic than PFOA

While the EU is expected to implement a total ban on PFAS between 2026 and 2027, the UK has taken a more targeted approach, focusing on banning individual chemicals rather than the entire class – a strategy that could have serious consequences. PFAS produced as far back as the 1940s are still contaminating water sources today. Moreover, a banned PFAS compound can be slightly modified

and reintroduced to the market, meaning that regulating chemicals individually is unlikely to keep pace with the scale and persistence of this problem.

## From everyday uses to persistent pollution

The unique properties of PFAS have enabled their use in a wide range of applications.

### *Firefighting foams*

Historically, firefighting foams contained both PFOS and PFOA. These chemicals acted as surfactants, helping the foam spread effectively over fires. In 2011, the EU banned PFOS in firefighting foams, but PFOA remained in use until its scheduled total ban in July 2025. The slow and staggered approach to banning these chemicals has left many sites where fire drills were routinely conducted – such as airbases, airports and training facilities – heavily contaminated with PFAS. These chemicals have infiltrated groundwater, soil and, in some cases, drinking water supplies.

As a response, alternative foams are now being used. One example is soybean-based foam, which extinguishes fires through a similar smothering and cooling mechanism as PFAS-based foams.

### *Non-stick coatings*

PFAS are perhaps most famously used to create non-stick coatings, such as Teflon. Teflon is made from polytetrafluoroethylene (PTFE), a PFAS chemical traditionally considered less harmful due to its fully polymerised form, high molecular weight and chemical stability. Currently, there are no regulations requiring companies that produce PTFE to disclose its production processes.

Producing PTFE involves the combustion of other PFAS chemicals, which provides a pathway for these substances to enter wastewater and the wider environment. While research on PTFE is more limited compared with shorter-chain PFAS, studies show that when PTFE is heated or chipped, it can break down into shorter-chain PFAS molecules. This is significant because PTFE-coated pans are routinely heated and chipped during everyday household use. Additionally, when these pans are disposed of and incinerated with other waste, they release short-chain PFAS into the environment.

PFOA, previously used in PTFE production, was banned in 2019 under the Stockholm Convention, yet its legacy continues to pose environmental risks.

### *Outdoor gear and sportswear*

Thanks to their stain-resistant, waterproof and fire-resistant properties, PFAS – particularly PFOA and PFOS – have been widely used in outdoor gear and sportswear, from tents and ski jackets to smartwatch bands. Although their use has declined in the UK and EU following regulatory bans, it has not been eliminated. Most textiles and manufactured goods sold in the UK are imported from Asia, where PFAS regulations are far less stringent. As a result, products marketed as stain-resistant, fire-resistant or waterproof are still highly likely to contain PFAS, despite consumer expectations of safety.

## Hope for a PFAS-free future

Although PFAS are often called ‘forever chemicals’, this is not entirely accurate. While we currently have no way to remove them once they accumulate in the human body, scientists are developing methods to destroy PFAS before they reach this stage. One notable approach is electrochemical oxidation. Even more promising, certain species of *Acetobacterium* (a genus of anaerobic bacteria),

commonly found in wastewater, can break down some PFAS by cleaving their carbon–fluorine bonds. Groundbreaking research from July 2025 also revealed that bacteria in the human gut can accumulate PFAS and aid in their excretion. While these chemicals are poised to have a significant impact on public health in the near future, nature is already showing ways to dismantle them, once again offering a potential solution to a problem of our own making.

## Glossary

**Electronegativity** The measure of the tendency of an atom in a stable molecule to attract electrons within bonds towards itself. In a chemical bond, the atom with higher electronegativity tends to acquire a partial negative charge.

**Hydrophobic** Meaning ‘water-hating’, hydrophobic molecules are non-polar molecules that cannot interact with water.

**Lipophilic** Meaning ‘fat-loving’, lipophilic molecules are molecules that associate or dissolve in (non-polar) lipids.

## Practice exam questions

- 1 Compare the chemical reactivity of PTFE with a typical hydrocarbon polymer such as polyethylene (polythene). (2 marks)
- 2 Explain why the long-term stability of PFAS poses a problem for the environment. (2 marks)
- 3 Explain why banning only PFOS or PFOA may not eliminate environmental PFAS contamination. (2 marks)

*Answers are on the next page*

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### Answers

**1** PTFE is much less reactive because of the strong C–F bonds and so is resistant to acids, bases and heat. Polyethylene has weaker C–H bonds and is more susceptible to chemical attack and thermal degradation.

**2** PFAS resist degradation and accumulate in soil, water and living organisms. They can enter the food chain and drinking water, posing health risks such as liver damage, developmental problems and potential carcinogenic effects.

**3** Other PFAS with slightly modified structures can replace them and persist similarly. Also, existing PFOS and PFOA remain in soil and water for decades due to their chemical stability. So, a regulatory focus on individual compounds cannot keep pace with the wide range of PFAS.