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Feature

Forever problems

Perfluorinated and polyfluorinated alkyl substances (PFAS) such as Teflon™ were celebrated in the 20th century as major achievements of the chemical industry and found their way into tens of thousands of consumer products. Now their impact on the environment and human health is becoming a concern, and the search is on for methods to avoid, remove and replace them. **Michael Gross** reports.

On April 6, 1938 Roy Plunkett, a young chemist working for DuPont at the Chemours Chambers Works plant in New Jersey, USA, wanted to use the gas tetrafluoroethylene to try and make new chlorofluorocarbons for possible use in refrigerators. Although the weight of the gas tank seemed to indicate it was full, no gas came out. Plunkett opened the vessel with a saw and found its inside was coated with a waxy white substance. He realised that the tetrafluoroethylene molecules must have polymerised in the same way that unsubstituted ethylene can polymerise to form polyethylene, which was already known then. Essentially, the polymer he discovered by accident was a version of polyethylene (polyethene in IUPAC nomenclature) with all the hydrogens replaced by fluorine. It is thus a perfluorinated carbon compound, as opposed to polyfluorinated compounds where several or many (but not all) hydrogens are replaced by fluorine.

Polytetrafluoroethylene was patented in 1941 and later trademarked as Teflon, but it was still expensive to make and no obvious application presented itself that was commercially viable. It found its first use in the Manhattan Project to build the atomic bomb, where it served in the shape of valves and gaskets resistant to the corrosive gas uranium hexafluoride.

The kitchenware use now associated with the material only emerged much later, after a suggestion from the French woman Colette Grégoire, whose husband had been using the material to lubricate his fishing gear. Her idea led to the Tefal-branded non-stick frying pans, whereas a separate development produced the Happy Pan in the US.

Today, millions of different per- and polyfluorinated alkyl substances are known and many of them are used commercially. Half of the amount produced industrially accounts for Teflon, half of which is used as insulation in electronics and high-end electrical equipment, such as in aviation and in medical devices.

Certain PFAS materials used in production have long been recognised as problematic and connected to a wide range of human health risks, including cancer, hormonal dysfunction and immune problems. Thus, perfluorooctanoic acid (PFOA, C8) was already under suspicion in the 1980s and 1990s. Starting in 2000, the lawyer Robert Bilott was able to expose that DuPont and 3M had been releasing PFOA into the environment even though their own research suggested that it was carcinogenic, at least to animals. PFOA has since then been widely banned, phased out and replaced. A notable exception is its continued use in firefighting foam.

Now, however, the ubiquitous presence of many chemicals from the PFAS family along with their natural stability have led to the compounds being labelled ‘forever chemicals’ and considered a major part of the problem posed by chemical pollution, one of the key areas where we have already exceeded planetary boundaries (Curr. Biol. (2022) *32*, R141–R143).

Everywhere chemicals

Because PFAS are so indestructible, they are also everywhere chemicals. They are now detectable in marine and freshwater environments, in wildlife and in the blood of every person tested in the US. A recent UK investigation by Watershed Investigations, the Marine Conservation Society and the Guardian also revealed widespread contamination in wildlife (https://tinyurl.com/5xx2wkhv).

Based on an environmental standard setting a maximal tolerable concentration of PFAS in fish tissue at 9.1 µg/kg (ppb), the investigation found that around half the animals sampled exceeded that threshold. If a lower limit of 0.077 ppb were applied, as is currently being considered by the EU, around 92% of these animals would be contaminated in excess of that limit.

Aquatic mammals had the highest contamination levels, with otters (*Lutra lutra*) reaching 9,962 ppb, harbour porpoises (*Phocoena phocoena*) 2,420 ppb, grey seals (*Halichoerus grypus*)

Emergency response: Firefighting foams containing PFAS have been used for decades. In locations with regular fire drills, the substances have accumulated in the environment. (Photo: Senior Airman Brett Clashman, US Air Force/Wikimedia Commons.)

Sentinel species: Eurasian otters (*Lutra lutra*) have been shown to be highly contaminated with fluorinated chemicals. (Photo: Ashley Buttle/Flickr (CC BY 2.0).)

357 ppb and dolphins 78 ppb. Levels in birds were up to 368 ppb, in foxes up to 129 ppb and in fish 41 ppb.

In a detailed study of the possible sources of PFAS contamination in otters, Emily O'Rourke from Cardiff University, UK and colleagues correlated the PFAS contaminations to the distance from Teflon-producing industry, to the PFAS load entering water treatment plants and to the proximity of arable land (Environ. Sci. Technol. (2022) *56*, 1675–1687). Their findings suggest that PFOA in particular was found in the environment near the plant that used this compound in the production of Teflon. For PFAS in general, the application of sewage sludge to agricultural land was identified as a major pathway for PFAS to enter the environment and the freshwater system. The findings also suggest that the otter is a useful sentinel species for the detection of this kind of pollution.

More recent data obtained by Watershed Investigations also showed high levels of PFAS contamination in sewage sludge destined for use on agricultural land. US investigations have also linked PFAS in sewage sludge to its occurrence in dairy products.

Another persistent source is the use of PFAS including the known carcinogen PFOA in firefighting foam. The company 3M, which has produced such foams for decades but has now stopped doing so, has been involved in various litigations around its claims that the material was harmless and biodegradable. PFAS pollution is especially high in locations where such foams are used frequently, such as firefighting training grounds, as well as near airports, which tend to have frequent fire drills.

One surprising contamination hotspot is Jersey (Channel Islands), where the local airport used foams with PFAS in weekly firefighting exercises. The chemicals found their way into the water supply, such that many residents of the island now have dangerously high levels of PFAS in their blood. A scientific advisory panel appointed by the Jersey government came to the conclusion that the government should look into the possibility of offering bloodletting as a way to reduce the concentration in the blood, even though it is far from clear whether this will protect those concerned from PFAS-induced harm. There is also a treatment with the cholesterol-lowering drug cholestyramine under consideration, which may be more efficient but also has a risk of side effects.

Pollution policy

With their ubiquitous presence and continued use, PFAS are likely to reign as a dominant pollution problem of this century. Due to their massive economic importance, politicians haven't dared to take drastic measures yet, but a ban may eventually become inevitable.

So far, some PFAS compounds have become part of the Stockholm Convention on Persistent Organic Pollutants, which came into force in 2004 and outlawed just nine notorious chemicals out of 12 listed but has a mechanism for adding more. The original list included the pesticides aldrin, chlordane, dichloro-diphenyl-trichloroethane (DDT), dieldrin, endrin, heptachlor, hexachlorobenzene, mirex and toxaphene, as well as the industrial chemicals hexachlorobenzene and polychlorinated biphenyls (PCBs).

In 2009, perfluorooctane sulfonic acid (PFOS), its salts and perfluorooctane sulfonyl fluoride were restricted under the Stockholm Convention with an exemption for several specific applications including firefighting foam and the control of leaf-cutting ants.

In 2019, PFOA as well as its salts and derivatives were banned, again with various specific exemptions. In 2022, perfluorohexane sulfonic acid (PFHxS) along with its salts and related compounds were added to the list without exemptions.

The European Commission is currently pondering a wide-ranging ban on the production and use of PFAS. In February 2023, the member states Germany, Denmark, Sweden and the Netherlands, along with non-member Norway, proposed a blanket ban for 2026, with substance-specific grace periods between 18 months and 12 years to allow companies to introduce replacements for the more than 10,000 products currently containing PFAS.

Producers of PFAS started lobbying against the proposal to such an extent that a group of Green members of the European parliament felt the need in January 2025 to launch a petition in favour of a ban.

In the US, initiatives to regulate PFAS and limit the discharge of the chemicals into the environment were started under the Biden administration but were among the first measures to be stopped by the executive orders after the Trump takeover.

Litigation appears to be a more successful way of stopping production in the US than regulation. So far, lawsuits have brought settlements worth more than $11 billion and have driven the major producer 3M to give up on PFAS products altogether. If the EU ban fails to materialise, law firms specialising on environmental litigation may expand this approach to Europe.

The EU Drinking Water Directive currently limits the permissible amount of PFAS in drinking water to 0.5 ppb and the sum of 20 specific PFAS to 0.1 ppb. From 2026, drinking water will be assessed and compliance with these limits enforced.

Conspicuous consumption: Many consumer products, from lipsticks to ski wax, contain PFAS. The EU is now considering a ban on these uses. (Photo: Ivan Radic/Flickr (CC BY 2.0).)

Cleanup

Even if all PFAS production were to be phased out from 2026, those already produced will continue to damage human health and the environment for a long time, if not quite forever. Products now in use could enter the waste disposal streams at any time, and the challenge will be to stop their PFAS content from escaping into the environment.

Current filters in water treatment plants, for instance, are clearly insufficient, as the widespread occurrence of PFAS both in sewage sludge and in the freshwater system has shown. Although filtration methods for organic pollutants exist, these have proven inefficient, especially for the short-chain PFAS molecules. Given the diversity of PFAS types, it is also a challenge to cater for the very different mixtures of chemicals that may occur in different contexts.

In a recent report of progress towards better PFAS filters, Nebojša Ilić from the Technical University of Munich, Germany and colleagues analysed the performance of several especially designed zirconium carboxylate metal–organic frameworks (MOFs) grafted with low-cost polymers as adsorbents for short-chain PFAS such as C8 (Adv. Mater. (2024) https://doi.org/10.1002/adma.202413120). While the authors have obtained promising results in terms of removal efficiency even at ppb concentrations, they caution that much more research and development will be required before such MOFs could be employed as filters in water treatment plants.

Another recent report raises the hope that the ‘forever’ can be taken out of forever chemicals with bioremediation approaches. Mindula Wijayahena from the University at Buffalo, USA and colleagues have identified a bacterial strain that is able to metabolise certain PFAS molecules if no other carbon source is available (Sci. Total Environ. (2025) *959*, 178348).

The researchers studied *Labrys portucalensis* F11, an aerobic bacterial strain that was isolated from the soil of a contaminated industrial site in Estarreja, Portugal. The strain has previously been shown to metabolise certain fluorinated chemicals and even to release fluoride from the perfluorinated methyl group in fluoxetine. For the new study, the researchers chose to test the species on the degradation of PFOS because this PFAS compound is one of the major dangers in terms of toxicity and pollution levels, although they also included other compounds for comparison. They found that, in the absence of other carbon sources, F11 can cut down and defluorinate the carbon chains of both fully and partially fluorinated molecules, including those with sulfonyl and carboxyl headgroups.

The degradation is a very slow process, however, taking place on the timescale of months, underlining that PFAS aren’t an ideal nutrient for the bacterium. The shortest period after which the researchers observed a significant degradation of PFAS was 100 days. After an extended exposure time of more than six months, the bacterium had even removed the fluorine from some of the metabolites it created in its first attack on the pollutants.

The researchers now hope to find ways of speeding up the bioremediation process and making it more efficient. Again, it will likely be a long time before anything based on this observation can find practical applications in the so-called bioaugmentation of water treatment processes or the bioremediation of contaminated soil. In real-world applications, the fact that the bacterium appears to only target fluorinated molecules if no other carbon source is available will surely be a major hurdle to its use.

In the meantime, a rapid stop on producing, buying, using and throwing away all those tens of thousands of products with PFAS in them is the only thing we can do to stop the forever chemicals from accumulating further and building up planet-wide forever problems.

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