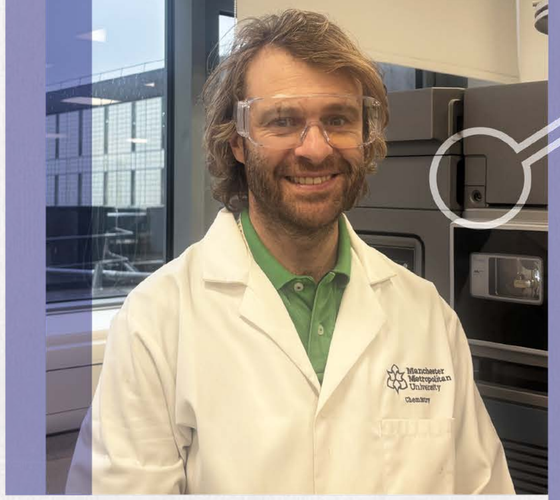


Special Series
PFAS Analysis

A special collection of recent stories exploring the science, regulation, and emerging solutions shaping the future of PFAS analysis

the Analytical Scientist x GL Sciences

PFAS: New Frontiers, Emerging Solutions

Launching our new special series, environmental chemist Chris Higgins reflects on progress, pitfalls, and the path toward meaningful solutions to the PFAS problem

There is growing awareness – among both specialists and the public – of the risks posed by per- and polyfluoroalkyl substances (PFAS or PFASs). These "forever chemicals" persist in the environment, bioaccumulate up the food chain, and are found in everything from medical devices, to food packaging, to rainwater. At the same time, toxicology data continues to build a clearer picture of their potential health impacts.

Chris Higgins, environmental chemist at the Colorado School of Mines, USA, remembers exactly where he was when he first heard about PFAS. "I was standing in my kitchen in a rental just outside of Boston – back in 2001," he says. Higgins was about to drive across the country to start a Masters with Dick Luthy (who, sadly, recently passed away) at Stanford, but his one-year Dean's fellowship wasn't tied to a specific project. "I called up Dick and asked him if there are any topics I should be thinking about." Luthy replied: "I've heard about these things called fluorochemicals. I think they might be big – you should look into them."

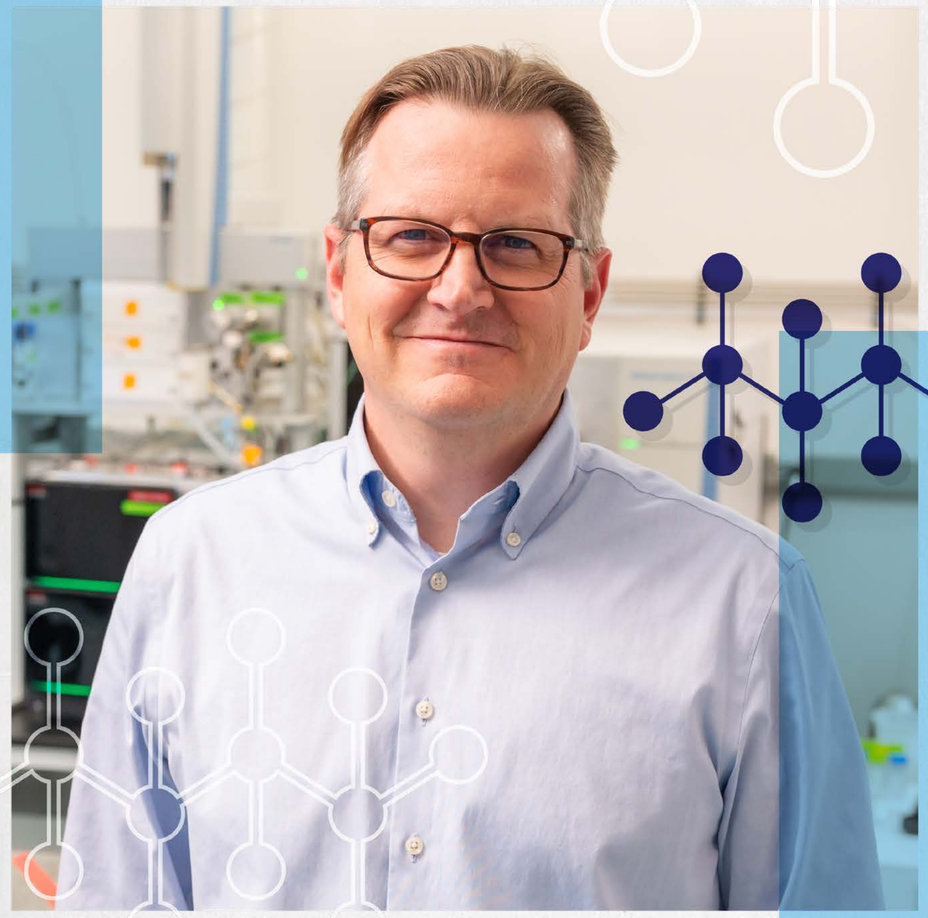
The suggestion stuck. As it happens, Craig Criddle had moved from Michigan State to Stanford a year or two earlier, and he had co-authored a fairly seminal review around 1997 called Fluorochemicals in the Biosphere. "That paper really kicked off the idea that people should start looking at these chemicals," says Higgins. It was Criddle who suggested that Luthy, as someone familiar with PCBs and DDT, ought to be looking at fluorinated compounds. "Everyone else in Dick's group was working on PCBs, but I came in and he basically said, 'I don't know anything about them, so let's figure out what we can learn together,'" he says.

The Luthy lab was one of the first environmental engineering labs in the US to receive funding for an LC-MS instrument. "At that time, LC-MS systems were rare in environmental engineering labs," says Higgins. His first paper, co-authored with Jennifer Field, looked at PFAS in sediments and sludge. After that, Higgins shifted more into studying PFAS fate – how they interact with soils and sediments – as well as their bioaccumulation. "Over the past 20–25 years, my career has largely followed those same threads: analytical methods, fate and transport (how the chemicals move through the environment), and some work on human exposure and bioaccumulation," he says. "The only major area I wasn't involved in at the beginning but have moved into more recently is treatment – the 'how do we fix this?' side of the problem."

This question – against a backdrop of regulatory uncertainty, heightened consumer awareness, and mounting litigation – is what we will tackle as part of a special series of articles: PFAS: New Frontiers, Emerging Solutions. In this interview, Higgins reflects on how far we've come – and explores what analytical scientists must do next to meet the PFAS challenge.

How has our understanding of PFAS evolved since you first began studying them?

When we first started, I don't think we fully appreciated the sheer



diversity of the products, or the range of PFASs that were out there. For example, in the early days, we didn't pay much attention to what I'd now call the TFA subgroup – essentially, compounds that have trifluoromethyl groups and thus have the potential to transform into TFA. There are a lot of them. Trifluoromethyl groups are quite common in pesticides, pharmaceuticals, and so on. We were aware of them – I remember seeing references to things like trifluralin – but it felt like a separate topic.

And to some extent, I still think of it that way. When we talk about PFASs today, there's this category of long-chain PFASs – which is what most people think of when they hear the term – and they tend to be the most problematic. They've been added to the Stockholm Convention, and their bioaccumulation and toxicity are much better established.

Then there are the short-chain compounds – some of which are still in use – and the ultra-short ones, which would include TFA. From my perspective, each of these categories comes with very different issues and concerns. As much as we'd like to group all PFASs together, the reality is that when you start dealing with TFA and TFA precursors, the complexity ramps up so quickly that it almost requires an entirely separate conversation. It's a very different challenge compared to the substances that originally drove interest in the field – things like PFOS and PFOA.

How have analytical methods for detecting and quantifying PFAS evolved since your early work?

LC-MS has become a lot more common. When I was learning, everyone used to say, "You should learn GC-MS first – and then you can move on to LC-MS," because GC-MS was considered the foundational technique. I think that's completely flipped now. These days, most people doing environmental mass spectrometry start with LC-MS. Honestly, it's a bit easier – you can take a water sample, put it directly on the instrument, and start seeing results.

I remember when high-resolution systems started to be discussed as potentially useful in environmental work. High-res instruments had been around for a while, but their application in this field was just beginning. I got my first high-res system around 2015 or 2016 – about ten years ago now – and today almost everything we do uses high resolution.

We still have a triple quadrupole system in the lab, but high-res instruments have really proven their value for environmental work. And for PFASs in particular, they've been transformative – the sensitivity now is so high that we can measure incredibly low concentrations in environmental samples. Triple quads are still extremely sensitive, but many high-res systems are as well.

I would never have imagined having four LC-MS systems in my lab when I first started. But honestly, at this point, we probably need more!

What are the biggest analytical challenges we still face when it comes to detecting and understanding PFAS?

Some of the most interesting – and honestly sometimes frustrating – challenges come from the fact that we're probably still not looking at all the right compounds.

There was a period a few years ago when people would almost compete over who had the longest target analyte list. But I'm not sure how helpful that was. Especially in targeted work, where you can't just "look for everything" the way you can with high-resolution instruments.

There's still a bit of that list-focused mentality, partly because of all the standardized method lists – EPA Method 533, 537, 1633, and on the gas phase side, the OTM 45, 50, and 55 methods. Those methods aren't bad, but they're not necessarily the be-all-and-end-all that some people treat them as. I think there are probably important groups of compounds missing from those lists – especially depending on the type of site or sample you're dealing with.

So, targeted lists are expanding, but there's probably a point of diminishing returns. We might not detect many additional compounds except at very low levels, so we *should* focus on prioritizing the compounds that really matter – the ones that we should be measuring. The size of the list doesn't matter if it doesn't contain the right compounds. And given how many PFASs exist, the incredibly low levels we can detect, and the fact that there's probably not a square meter of the planet without a PFAS molecule on it…

I think we're moving more toward routine monitoring. That will drive things like remediation goals and regulatory decisions. But for that to be practical, we need more automation. Right now, something like solid-phase extraction is really helpful – but also extremely time-consuming. Jennifer Field really pushed me to try direct-injection analysis wherever possible because it minimizes sample prep and speeds things up. She does it slightly differently from how we do it, but the principle is the same: you can process far more samples much more quickly. And as we shift further into large-scale monitoring scenarios, I think that kind of approach is going to be incredibly valuable.

How would you characterize the current landscape of PFAS remediation?

If we accept what toxicologists tell us about appropriate regulatory levels, then I do think we generally have the tools needed to provide

people with clean water. There's particular concern around some of the regulatory levels being discussed in Europe, especially regarding TFA, simply because it's so prevalent. But with that issue aside, I do think we have the core technologies we need. The main challenge is making them cost-effective. But if we're talking about remediation more broadly – restoring the environment to its original state, not just making water safe to drink – that's where the bigger challenges lie.

We have to think about where people's exposure actually comes from. Robin Vestergren from the Swedish Chemicals Agency did a study a few years ago that involved what I'd call exposure reconstruction – and my group has been some of that too for impacted communities too. What he showed, and what we've also seen, is that when drinking water is contaminated, yes, that's a major exposure route – but beyond drinking water, the biggest route is *food*.

It's things like fish, eggs, and other animal products, at least for the long-chain PFASs. So if the goal is to reduce human exposure, it's not enough just to clean up water; we also have to be thinking about food. If you're a food company with any animal-derived ingredients in your products, it's probably wise to start looking into PFASs – both what might be present in the food itself, and what might come from the processing equipment or packaging. Developing faster, easier, more reliable ways to analyze food for a broader suite of PFASs – beyond just PFOS and PFOA – is something we absolutely need to do.

Site remediation is another issue. The US Department of Defense (DoD) has a large number of impacted sites with contaminated groundwater and soil due to their use of aqueous film forming foam (AFFF), and they're trying to clean those up, for example. There are some really exciting advancements happening in that space. But it's important to remember that the DoD wasn't the only user of AFFF.

The big question for remediation is scalability. And this is where analytical chemistry really comes in: we need to be sure we're not turning one problem into another. For example, there was a moratorium here in the US on the disposal of DoD PFAS-impacted materials in hazardous waste incinerators, as there were reports of elevated levels of some fluorochemicals around those incinerators. That raised questions: were they fully destroying the PFASs, or only partially combusting them?

While there are some non-thermal PFAS destruction technologies, most of the promising ones rely on applying large amounts of energy and/or heat. That means they can generate volatile products – and we need to be sure we're not simply creating a new set of airborne contaminants in the process. If the PFASs aren't completely broken down, they may exit into the air and become a new source of exposure – and they could have a completely different toxicological profile from the original compounds.

We call those products of incomplete destruction, or PIDs. There's been a lot of analytical work to determine how best to detect them: do we use EPA methods that capture emissions on a sorbent or in a SUMMA canister, followed by direct analysis? Or do we try real-time measurements – things like FTIR or chemical ionization mass spectrometry (CIMS)? These are the kinds of analytical tools that need more attention.

For more traditional contract lab work, the path is clearer: we'll be monitoring water, soil, fish, blood, and probably food for years to come – that's becoming routine. What's less clear is how best to analyze destruction processes – whether at hazardous

waste incinerators or municipal ones, which are also fed consumer products containing PFASs (like old furniture with stain-resistant coatings that ends up in landfills). Are we getting emissions from those? Are we fully destroying the PFASs?

I'm just starting to get involved in this work myself, but it's become clear that any remediation project involving destruction technologies really needs to consider potential air emissions.

For students entering the field today, where do you see the biggest opportunities to contribute meaningfully to PFAS research and solutions?

In terms of *skills* or *approaches*, the first thing I'd say is: learn mass spectrometry, as it's going to be with us for a long time. There will certainly be non-mass spec tools emerging, but there's a reason mass spec has become the gold standard – it works incredibly well for identifying a wide variety of these compounds, and we understand it deeply. As much as I'd love to see sensor-based approaches, I don't think we'll get there in the near future – at least not broadly. Maybe for very specific PFASs, but not for the full diversity of compounds. Mass spec gives you that breadth.

We haven't talked much about total organic fluorine or related bulk measures. Personally, I'm not a huge fan – they can be useful in certain applications, especially as screening tools, but they don't give you the specific information you need. If you start seeing high levels of organic fluorine everywhere, it becomes less informative. You need to know what's there, not just that something *is* there.

Also, don't be afraid to go out into the real world. If you want to do environmental work, go collect real samples. Embrace the complexity of the real world. Measuring a clean soil that you've spiked in the lab, or a clean fish liver sample you've dosed, is not the same as going out and collecting real environmental samples and bringing them back to the lab. People sometimes get nervous about that because it can be messy and difficult – but for a lot of my students and postdocs, that real-world work has been the most eye-opening.

The way I see it, the real world will tell us what the actual problems are – but only if we go out and look. That's been my guiding principle for all the environmental analytical work we do: let the environment itself guide the science.

Why is it so important for analytical chemists to engage with engineers, toxicologists, and other fields when working on PFAS?

If you want to have an impact, you've got to collaborate with people in other disciplines.

What we measure in water is directly relevant to what toxicologists need to know – because that's the water people drink, or the water fish live in before we eat them. You can't separate those pieces.

In the remediation space, too, there have been plenty of – I wouldn't call them false starts, but let's say premature excitement. People get excited about a result where they think they've treated or destroyed a compound only to later find out that the analysis wasn't exactly wrong, but the chemicals didn't behave in their system the way they expected. Maybe the compounds were sticking to something unexpectedly, or volatilizing in a way they assumed they wouldn't – some of them *can* be volatile under certain conditions.

It's only when analytical chemists interface with engineers or toxicologists that you can confirm whether those results are real or just experimental artifacts. That's why I'd say to analytical chemists: don't be afraid to engage with other fields.

Recognize that what happens in a simple test tube – partitioning to the glass walls, loss to the vial headspace – involves the same physical-chemical processes that control behavior in real-world remediation systems or toxicology experiments. If you understand those processes as an analytical chemist, you can help engineers and toxicologists do better, more accurate work.

As we continue to detect PFAS in more places and at ever lower levels, how should analytical scientists think about the connection between measurement, harm, and public communication?

PFASs are a hugely diverse class of compounds with a wide range of toxicities. The longer-chain compounds are clearly more bioaccumulative, and we have fairly good toxicological data for some of them – but not all. When we find man-made chemicals in people's blood – chemicals they never chose to put there – it naturally raises concern. Even if toxicity isn't fully established, evidence of exposure matters, and people deserve to be informed. Today, we can easily detect PFASs in water, blood, and food, but that doesn't necessarily mean those sources are unsafe – it just means we need to understand our exposure.

As analytical chemists, we can measure almost anything, almost anywhere. There's value in that, but we also have to be careful about how we communicate what those numbers mean. We have to collaborate with risk assessors and toxicologists to ensure that a measurement doesn't automatically translate into alarm.

Just because it's there doesn't necessarily mean it's bad – and we need to be very careful and deliberate about how we convey that message.

Link
View references online

Captured Airborne PFAS Across Every Phase

FM4 enables multistage sampling of particulate, aerosol-bound, and vapor-phase PFAS for advanced atmospheric analysis.

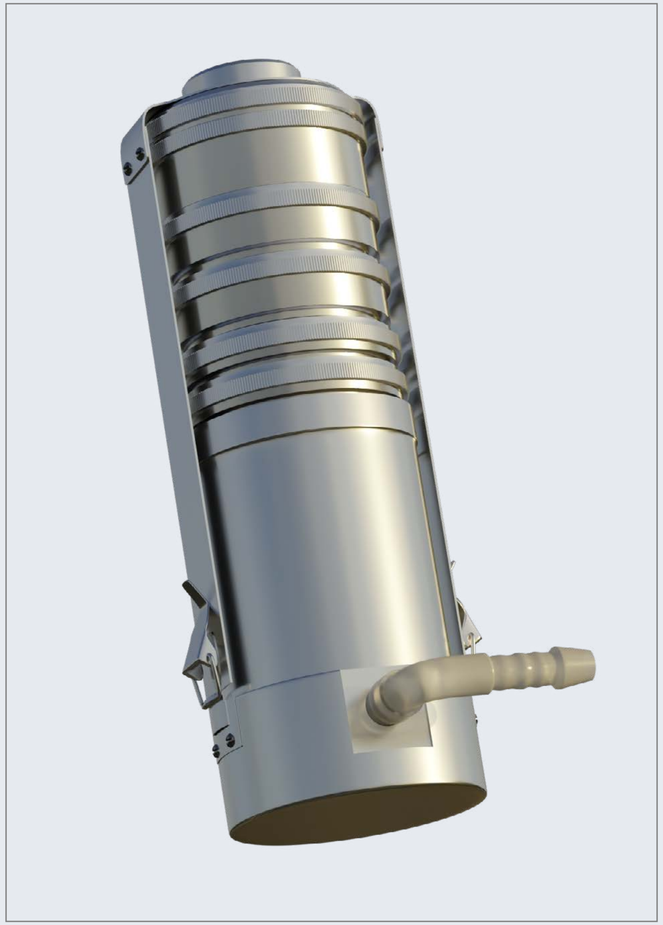
Airborne PFAS are increasingly recognized as an important pathway for long-range environmental transport. While waterborne PFAS contamination has been widely studied, atmospheric PFAS can move through multiple forms, including particulate-bound compounds, aerosol droplets, and vapor-phase neutral PFAS such as fluorotelomer alcohols.

GL Sciences' FM4 sampling module is designed to address this complex challenge. The FM4 system enables multistage collection of airborne PFAS in a single sampling event, using quartz fiber filters to capture particulate-bound PFAS, polyurethane foam to collect semi-volatile and aerosol-associated PFAS, and activated carbon fiber discs to adsorb vapor-phase compounds.

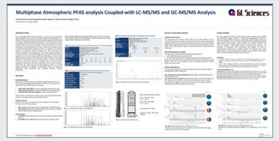
In this poster study, the FM4 module was deployed at a monitoring site in Japan under different meteorological conditions and sampling durations. The collected media were analyzed by both LC–MS/MS and GC–MS/MS, targeting a combined 54 PFAS analytes, including ionic and neutral compounds. The method achieved low ng/m^3-level quantification limits, with most analytes showing recoveries between 70% and 120%.

Field results demonstrate that atmospheric PFAS composition can vary significantly depending on wind direction and upwind source profiles. Under southwest wind conditions from a major coastal metropolitan area, higher concentrations of neutral PFAS, including 8:2 FTOH, were observed. Under northwest wind conditions from an inland source region, short- to mid-chain PFCAs were more dominant, particularly in the particulate fraction.

By separating PFAS across different airborne phases, FM4 provides valuable insight into atmospheric transport behavior, source apportionment, exposure risk assessment, and PFAS mitigation strategies. Combined with GL Sciences' LC and GC analytical technologies, the FM4 workflow offers a practical, field-deployable solution for laboratories investigating PFAS in ambient air.



LINK



Explore the FM4 workflow and advance your airborne PFAS monitoring capabilities.

PFAS Enters its Big Data Era

Jennifer Field explores new frontiers in the fight against PFAS: mining big data, tracing volatile emissions, and probing fluoropolymers through biomimetic tools

PFAS analysis has come a long way from the days of handwritten sample requests and improvised derivatization reactions. Few have witnessed that transformation as closely as Jennifer Field, whose work at Oregon State University has helped shape how scientists detect, quantify, and interpret these elusive chemicals.

Field was one of the earliest pioneers in the field. And like her colleague Chris Higgins – whom we interviewed in the first installment of our PFAS: New Frontiers, Emerging Solutions series – she remembers where she was, as a graduate student in 1985 at the Colorado School of Mines, when she first heard about PFAS. "I was in the office of my advisor, Don Macalady, who had this habit of picking up the phone even while he was in the middle of a conversation," she says. "One day, the phone rang, and he answered – it turned out to be an old elk-hunting buddy of his. While they were chatting, this friend – who also happened to work for a firefighting foam company – asked, '"Don, do you know anything about fluorinated surfactants?"'

At the time, Field was studying *non*-fluorinated surfactants. Don said, "No, but my graduate student does," and handed her the phone. "That was my introduction. I remember saying, 'Well, I don't know anything about that…'"

Later, Field went on to a postdoc, and then eventually became a new professor at Oregon State University. "As a new professor, you're always wondering what to study. And I thought, what about that fluorinated surfactant thing? Maybe I should look into it," she says. "Back then, there weren't many people studying PFAS – maybe one other group in the country had done a single piece of work. And now, of course, it has picked up tremendously – there are far more people working on PFAS than I could ever have imagined back in the early '90s."

Fast-forward to 2025, Field remains at the cutting edge of PFAS research, which she believes is entering a new phase – defined by the interpretation of the vast, complex datasets generated by today's instruments. In this interview, she argues that the future lies in treating spectra as chemical "fingerprints" and decoding them through collaboration, computation, and creativity.

How has the PFAS story evolved – especially from an analytical science perspective – since those early days?
In those early years, there wasn't much happening, very little literature to draw from, and no proper analytical standards at all. All of our early work was done without high-grade analytical standards. That's changed enormously, of course – that's been one of the biggest developments.

Our very first work actually involved injection-port derivatization of the carboxylic acids – which is a very unusual thing to do, but it worked remarkably well. I had carried this approach over from my work on hydrocarbon surfactants. If you take an anionic surfactant (the type most people focus on) in aqueous solution, add an ion-pair reagent, and do an ion-pair extraction – a technique that goes back many decades – the ion pair moves into a nonpolar solvent, in our case chloroform.

If you inject that into the hot inlet of a GC, you get instantaneous methylation (or ethyl, propyl, butyl – you can pick your derivative).

That's how we first analyzed the carboxylates. It didn't work on sulfonates – they're too electron withdrawing and act as good leaving groups, so that reaction just doesn't happen. So oddly enough, our first foray into PFAS was by gas chromatography. Eventually, though, we had to abandon that approach because not many PFAS are carboxylates that undergo that kind of reaction.

And again, this was all done without standards. I've got a fascinating collection of chemicals from those early days. Back then, I would literally write away for them. Chemical & Engineering News was a paper magazine, and in the center there were these tear-out cards. You could send those cards in to get free 3M fluorochemical kits – so I did. They even came with these great brochures explaining which are the carboxylates and which are the sulfonates.

That was incredibly helpful, and it's how we launched our early work – writing in for free samples (they weren't called "standards" then) that were really meant for people formulating products. But they became our first reference materials.

Of course, the language has changed completely since then. Today we talk about suspects, non-targets, and targets. Back then, everything was essentially non-target. Now, as analytical standards become available, compounds move from the suspect list to the target list – and that shopping list just keeps getting longer. These days you can buy, depending on who you ask, maybe 70 or 75 target PFAS. Everything else is "suspect," and those suspect lists are now huge. We've compiled a grand mash-up from nine different databases, and there are tens of thousands of suspects you can screen for.

None of that existed back in the day. And along with the lack of analytical standards, there were also no isotopically labelled standards for quantification – that's another major advancement.

So, in terms of how things have changed: we went from a brief GC phase to LC, and then standards started becoming available. But for the first ten years or so, nearly all studies focused on just PFOS and PFOA. People still focus heavily on them – which makes sense from a toxicology perspective – but it wasn't until maybe 10 or 15 years ago that researchers really started saying, "It's not just PFOS and PFOA."

That shift led to the development of the total oxidizable precursor (TOP) assay, which was a way to start wrapping our heads around all the other organic fluorine out there. That was an important addition to our toolkit.

Since then we've seen a lot of indirect methods emerge over the past 10–15 years – things like the TOP assay, combustion methods, total organic fluorine, extractable organic fluorine – because what we often find is that if you measure total fluorine and then compare it to targeted PFAS, the targets account for only a fraction of the total.

That tells us we still have a lot of work to do in identifying the unknown organic fluorine. And to fully account for it, we need to cover non-volatile and volatile fractions, and deal with classes that defy both traditional LC and GC methods – such as fluoropolymer monomers and the fluoropolymers themselves.

So really, we're still trying to understand the totality of fluorine in the environment – and that, for sure, remains a grand challenge.

Do you think current standardized methods – especially those used by regulatory agencies – are broad enough to capture the full diversity of PFAS in the environment?

There's definitely a lot of commonality across methods, as well as a strong push to make analytical approaches as uniform as possible – and I understand why.For example, making the analysis of water, sediment, plant material, and leachates all follow essentially the same method has the advantage of being widely deployable – it makes results more comparable, and it allows contract labs, academics, government agencies, and private companies to execute them consistently. That's a good thing.

But when you have a one-size-fits-all method, it can limit innovation – or at least reveal its limits. A good example is the ultra-short-chain PFAS, which are a big topic right now. Some of the standard methods struggle to capture them. There's a lot of ongoing work and many variations on the existing methods, but it's an example of how we'll have to adapt to go broader.

I like to think about an analytical method like a train. There's the engine – the first step – then a series of cars, and finally the caboose. Each step is optimized to perform a specific function and provide a certain quality of information. In environmental analysis, that first step is usually a tailored extraction to target specific molecules.

Right now, globally, there's a heavy focus on anionic PFAS – the negatively charged ones, like PFOS and PFOA. Those were the earliest known PFAS, and they've been the focus of decades of work in environmental monitoring, toxicology, animal studies, and so on. There's a reason for that: they tend to be mobile. Negatively charged molecules move readily through the environment, whereas positively charged ones tend to get stuck in soils and sediments, and therefore don't travel as far. So it made sense to spend so much time and effort on anionic PFAS. But here's the problem: if the "engine" of your analytical train – your first step – only selects anions, you'll only ever see anions; you're effectively covering one eye. If we want to

understand total fluorine, we need both eyes open – we need to see anionic, cationic, neutral, and zwitterionic molecules.

Most current methods are selective for negatively charged compounds right from the start, and that means we're probably losing information immediately. Now, if your goal is strictly to quantify PFOS, PFOA, and other anions, those methods are fit for purpose. But if you want to explore more broadly, to see a fuller range of PFAS and understand total fluorine, you can't only use a first step that selects for anions.

That's been our focus: developing broader methods that can capture a wide variety of PFAS – low to high molecular weight, anionic, cationic, neutral, and zwitterionic. We've been in discovery mode for, I'd say, about 15 years – very focused on using our analytical capabilities to broaden the scope.

And we've tried to think outside the box – for example, we were using ion-exchange-based separations and detection methods very early on, because it was never just about PFOS and PFOA for us.

How do you view the challenge of potential overload when it comes to the sheer number of chemicals that researchers can now measure?
That's a great question – and it's something that's changed dramatically over time.

Back in the day, it was one or five compounds. Then it became a dozen. Then 40. Now we're up to around 75 targets – and that's just from a "target" perspective, meaning: is molecule X present in your fish, your water, your air, whatever. That's a very specific kind of question, and you can answer it cleanly.

But there's probably a breakpoint. And I'll just admit it: analytical chemists are not *all* naturally inclined toward the big-data side of things – only some really want to dive into that space. But that's increasingly where the challenge lies: how do you deal with such a huge number of molecules?

Right now, most labs have their list of X number of targets, and that list shifts over time. But at some point you hit diminishing returns. We spend thousands of dollars a year – as do other labs – on labeled isotopes to build out our target lists. And at some point, that approach becomes hard to sustain.

So a few years ago, I made a decision – as have some other labs – to collaborate with people who work with *entire* high-resolution mass spec data sets. Yes, you can retrieve your targets (your PFAS list) from the data, and that's fine – we still do that. But you can also mine that same data for suspects from large databases. And beyond that, you can go fully non-targeted.

And then there's another level: you stop trying to identify everything at all. Instead, you treat the full data as a *fingerprint*. You don't necessarily know what every single peak is – but you use the entire pattern. And then you bring in collaborators in bioinformatics, advanced statistics, machine learning, and AI – they can help you interpret those complex fingerprints and tell stories from them.

At that point, you've essentially left the world of targets and suspects behind, and you're asking a different kind of question: *what is the overall chemical signature telling me?* That's the new frontier.

Are there any other emerging frontiers PFAS frontiers you'd like to highlight?
One area that's still relatively understudied is volatile PFAS – the gas-phase compounds. It's not entirely new, but compared to other PFAS research, it's had far less attention. Understanding their emissions and exposure routes is really important.

We've done some work on paints and consumer products. Here in the US, for instance, if you go shopping for interior paint, there's about a 30 percent chance it contains PFAS. Not that it's *PFAS-based* paint, but PFAS are used as ingredients. Why? Because of "low-VOC" paint formulations.

Now, "low VOC" doesn't mean "no volatiles" – it's a regulatory definition. It refers to volatile chemicals that don't react with ozone. Paint companies switched to compounds that don't undergo those VOC reactions. And that's what some PFAS, like fluorotelomer alcohols, are. They're so unreactive that they don't count as VOCs – and that's why they get used.

The result? When you paint a room, large amounts of these fluorotelomer alcohols can be emitted during drying. It's completely unregulated and invisible – unless someone goes and analyzes the paint, which is what we did. So a professional painter or even a homeowner could be exposed to quite a bit – and no one would know. And every time you wash your brushes, you rinse pulses of PFAS down the drain, which end up in wastewater.

This is a good example of how PFAS can slip in as substitutes – they give paints nice leveling properties, stain resistance, washability – all the things people want. But not all paints have them, which proves they aren't essential.

The challenge is that we often don't know they're there unless someone checks. So people are now asking: do we *need* them? But you need the political and regulatory will – and the knowledge – to drive those changes.

Another example is the semiconductor industry as another. It's a globally critical industry, and there are many processes for which

they simply haven't found substitutes for PFAS yet. There's a lot of effort in different parts of the semiconductor industry to understand their PFAS use and prevent releases – but it's a huge challenge.

They use PFAS across an enormous range of properties: from ultra-volatile greenhouse gases all the way up to polymeric PFAS. That creates a major analytical challenge – trying to cover that entire chemical space, from the most volatile compounds to the very high molecular weight materials that you won't detect on a typical LC-HRMS or GC-HRMS instrument.

And with the OECD now classifying fluoropolymers as PFAS, we analytical chemists face another challenge: very high molecular weight compounds are difficult to quantify. You can do qualitative work, but quantitative work is much harder.

Fluoropolymers, side-chain fluoropolymers, fluoropolymer oligomers – they're all extremely challenging to measure. And because of that, it's difficult to assess the real mass flows of these materials through commerce, wastewater, and the environment. So that's another significant frontier where new analytical approaches are really needed.

Finally, in our lab, we're doing biomimetic chromatography with PFAS now. We're using biological stationary phases and passing PFAS targets – and complex mixtures – over them. This allows us to predict interactions with phospholipid membranes, human serum albumin, and AGP (alpha-1-acid glycoprotein), which is a protein associated with the brain and with some disease states.

Biomimetic chromatography has been used in the pharmaceutical industry for a long time, but we're now applying it to PFAS – characterizing their behavior to better predict why certain PFAS accumulate in certain species and organs.

So that's an analytical twist that's taking us toward understanding their biological interactions. It's a new frontier, and an area of active work in our lab right now.

Do you think that we – as a society, but also as a community of analytical scientists – can actually deal with the PFAS threat?
Well, it depends on what "deal with" means.

For analytical chemists, the first step is always: before you can call something a problem, you have to *see* it. People often jump straight to asking about toxicology, but tox data doesn't grow on trees – it takes time, money, and commitment to generate.

So, the first part of any emerging contaminant story – whether it's PFAS or something else – usually comes from the people who first *detect* it somewhere it's not supposed to be: in wastewater, in air, in animals, in people. That discovery triggers a cascade of questions: "How did it get there? What form is it in? What are the routes of exposure? What does it do once it's in you?"

That's the sequence – documenting exposure, then assessing risk. But now, through analytical chemistry, we've documented that we have *vast* volumes of water, soil, and sediment – and in some cases, air. Because these molecules have been emitted for so long, they've now permeated almost every environmental compartment on Earth. They're present throughout the entire ocean column. They're in the Arctic – in the air, in the animals. That's why you see people like Ian Cousins (Stockholm University) saying we may have exceeded planetary boundaries.

And on that scale, no one has an easy answer for what to do about it. It's not just a scientific challenge; it's financial, political, and regulatory.

What you are starting to see, though, is people asking hard questions like: *Does this particular application really need to use PFAS?* REACH and the EU are far ahead in terms of looking at chemical hazards more holistically and trying to limit the release of substances with problematic properties. The US doesn't operate under the precautionary principle, so things work differently here, though that is starting to shift a bit.

There's also a lot of funding going into remediation now – it's a huge challenge, but it's where much of the investment is focused. And analytical chemists have an important role to play there too.

Do you have a main message you'd like to share with the analytical community when it comes to dealing with PFAS?
I'd emphasize most is the value of collaboration. I think building teams that bring together toxicologists, epidemiologists, exposure scientists, and engineers creates a really vibrant space to work in.

If you're in an analytical lab, get out of your lab – or invite people into it. Because working in an interdisciplinary space is incredibly rewarding. There's even sociology research on this: if you're someone who just wants to race to the top alone, collaboration might not be for you – but for many people, it's an enormously fertile and productive environment. You can do things together that you simply can't do alone.

And as an analytical chemist, embrace the big data world. There's definitely a generational shift happening – all the new students know R and Python. That's the way of the future. Go toward that light. Embrace it. It's how you'll get the most out of your instrumentation.

Sharper PFSA Elution. Cleaner PFAS Backgrounds.

Ion-exchange-only SPE and an activated-carbon delay column simplify reliable low-level PFAS water analysis.

Accurate PFAS analysis requires more than LC–MS/MS sensitivity. It also requires reliable sample preparation and effective control of system-derived PFAS background.

GL Sciences' application note demonstrates a PFAS workflow using InertSep MA-2, a weak anion-exchange SPE cartridge based on methacrylate polymer with diethylamine functionality. Unlike mixed-mode reversed-phase/WAX sorbents, InertSep MA-2 relies on ion-exchange retention without a reversed-phase mode. This enables a clean, sharp elution profile for PFAS, including perfluoroalkyl sulfonic acids such as PFBS, PFHxS, and PFOS. In the study, PFAS compounds in water were extracted with InertSep MA-2 and analyzed by LC–MS/MS, achieving excellent linearity and repeatability across low-ng/L concentration ranges.

The workflow also addresses one of the most persistent challenges in PFAS analysis: background contamination from LC system components. GL Sciences' Delay Column for PFAS is packed with high-purity activated-carbon beads and is installed before the autosampler. Compared with a conventional C18 delay column, the activated-carbon delay column sufficiently separates system-derived blank peaks from sample-derived analyte peaks while adding virtually no pressure to the LC system. In the reported comparison, the system pressure remained unchanged at 19.8 MPa with the Delay Column for PFAS, while a C18 delay column increased pressure to 23 MPa.

Together, InertSep MA-2 and Delay Column for PFAS provide a practical solution for laboratories seeking cleaner PFAS profiles, reduced background interference, and a more robust LC–MS/MS workflow for water analysis.

LINK


GL Sciences

Analyses of Per- and Polyfluoroalkyl Substances in Water Using Ion Exchange Solid-Phase Extraction and LC–MS/MS with an Activated-Carbon Delay Column

Download the application note and see how GL Sciences improves PFAS workflow reliability.

PFAS Bioaccumulation: The Biology of Forever

Carrie McDonough explores how PFAS move, bind, and transform within us – redefining what exposure really means

The conversation around PFAS exposure and risk assessment often focuses on the prevalence of these compounds in our environment and their potential toxicity in the human body. However, the bridge that connects exposure to potential health impacts is bioaccumulation: understanding how PFAS move through the body, bind to proteins, and transform into new forms.

"Traditional risk models assume that chemicals accumulate in fatty tissues – in the lipids – and that their distribution is governed by hydrophobicity and affinity for organic carbon. PFAS don't behave that way," says Carrie McDonough, Associate Professor of Chemistry at Carnegie Mellon University, USA, whose work focuses on exploring the hidden biology of PFAS. "They interact with transporter proteins, bind to phospholipids, and engage in more polar interactions, so the classic POPs (persistent organic pollutants) models don't really apply."

In this third installment of our PFAS: New Frontiers, Emerging Solutions series, McDonough argues that we need new models that capture these unique behaviors – especially for assessing long-term, low-level chronic exposures like those from drinking water. "Otherwise, we're not accurately representing what the body is actually experiencing over time," she says.

How did you first find your way into PFAS research?

I come from a fairly multidisciplinary background – which I think is becoming increasingly common among people in environmental research. I started out in chemistry for my bachelor's degree, then worked in industry for a while. That's where I began doing mass spectrometry – eventually running an analytical lab at an environmental consulting firm. I absolutely loved it – especially the mass spectrometry – but I didn't enjoy doing the same analysis over and over again. I wanted to go back to school and keep learning.

When I started looking at graduate programs, I realized that if you wanted to do advanced mass spectrometry for water analysis or environmental contaminants, those programs were rarely in chemistry departments. Chemistry programs tended to focus on atmospheric, basic, or pharmaceutical chemistry – not the kind of work I wanted to do. That's still a challenge for undergrads today: figuring out where to go next if they want to pursue this kind of research.

So I ended up getting a PhD in oceanography – which, by the way, is where a lot of really good analytical scientists come from. I think that's because in oceanography you study extremely low trace-level chemicals that change by tiny amounts, so you need strong analytical skills.

I worked with Rainer Lohmann at the University of Rhode Island, doing emerging organic contaminant research in an oceanography school. He wasn't doing PFAS work at the time, so I studied a wide range of other contaminants – synthetic musks, flame retardants, organophosphate flame retardants, and so on. It was a great way to learn environmental chemistry because I had to understand how structural differences affect analysis, fate, and transport.

When I finished my PhD in 2017, nearly every postdoc position I looked at focused on PFAS. It was becoming a major concern, with lots of federal funding available, so all the opportunities were in that area. I was also really interested in high-resolution mass spectrometry. Up to that point, I had only used single quad and triple quad systems – never QTOF or other high-resolution instruments – and I wanted that experience. So I joined Chris Higgins' lab, where most of the work was PFAS-focused. As a postdoc, I led much of the biological analysis work – including human serum analysis (a first for the lab) and mouse tissue studies from dosing experiments in collaboration with Jamie DeWitt, who's now at Oregon State. That experience got me deeply into both high-resolution mass spectrometry and toxicokinetics and chemical biology – which remain big parts of my research today.

It wasn't that I deliberately chose PFAS because they fascinated me – though they are fascinating – it was more that the field moved that way and I moved with it. Nevertheless, PFAS are fascinating. Due to the fact that there are thousands of compounds with different properties, you get a broad view of fate and transport – as long as you don't focus solely on perfluoroalkyl acids. You get to use a wide range of instrumentation and consider many different properties, which I really enjoy.

Still, every time I write a proposal or plan a new project, it's always PFAS – and then I try to include other contaminants as well. Partly that's because I train students, and I want them to think beyond PFAS: to learn how to do PFAS analysis, but also to ask, "What's next?" What will they be studying in 20 years if they start their own lab? That broader mindset is important, and I try to instill it in them.

What makes PFAS such a difficult – and interesting – problem to tackle from an analytical perspective?

One of the first things that really intrigued me was the unidentified organofluorine question. You can measure total organic fluorine in a sample, and then measure what you can detect with LC-MS/MS – and those numbers often disagree by a lot. There's usually a big fraction we're not identifying, across all kinds of environmental samples.

What I find especially fascinating is how this plays out in biological samples. When I was setting up my lab at Carnegie Mellon, we reviewed every paper we could find – from the early 2000s onward – that measured organofluorine alongside targeted LC-MS/MS, and then calculated the unidentified fraction. The range was remarkable: in human samples, some studies found 0 percent unidentified, others 100 percent. And over time, the unidentified organofluorine fraction seems to be increasing. It also appears to be greater in women than in men, and it often has an inverse relationship with total organofluorine. If you live in a highly contaminated area – say near AFFF contamination – you're more likely to explain a larger portion of your PFAS burden. But if you're part of the general population, exposed mainly to diffuse sources and consumer products, you're less likely to explain much of it.

That's what fascinates me – why our current methods still don't close that gap. Many of the techniques I learned from Chris Higgins, and still use, haven't fully resolved it. Moving from LC-MS/MS to high-resolution LC-MS adds thousands of compounds to your analyte list, but it doesn't necessarily bring us closer to explaining the difference between what we can see and that unidentified organofluorine number. Some of that gap may exist because we can't properly quantify the unknown compounds – we can do semi-quantitation, but not enough to explain the missing mass. Fluorinated pharmaceuticals are often cited as contributors, and they probably are, but they can't explain everything.

In that same review, we saw large unidentified organofluorine fractions in aquatic organisms and invertebrates. Most pharmaceuticals break down fairly quickly in the environment – they either mineralize or degrade into trifluoroacetic acid (TFA). If they're ending up as TFA, that's significant, because it represents another contamination pathway.

So this whole question of unidentified organofluorine has become a compelling challenge for me: how do we measure organic fluorine and targeted PFAS together, and actually close that gap?

During my postdoc, I co-wrote a short critical review on this with Chris Higgins and Jen Guelfo. We looked at all the different methods for measuring the PFAS "universe," and showed how the more specific your method gets, the smaller your slice of that universe becomes. If you want high certainty, you measure a small fraction of the total. If you aim to capture total organofluorine, you gain breadth but lose specificity – you don't know what the structures are.

I still rely mainly on high-resolution approaches, but we're pushing further – trying new sample-introduction techniques. For example, we're starting to use GC-APCI to look for highly soluble, ultra-short-chain compounds and assess how much they contribute to the unidentified fraction. That kind of question – trying to solve the mass balance and understand what we're missing – draws many analytically minded researchers into PFAS work.

From the high-resolution perspective, there are other exciting directions too, like using clever filtering methods: by mass defect, by homologous series, and now, with ion mobility spectrometry, by

size versus mass. PFAS are smaller, but heavier than hydrocarbons of the same mass, so they cluster in a distinct "PFAS region" in ion-mobility space.

We can isolate that PFAS region from complex samples, which increases confidence in our identifications. Those kinds of smart filtering approaches make the problem feel solvable – even if it remains incredibly complex.

Since your "trade-off between selectivity and inclusivity" paper, how much progress have we made – and do we need new tools or just smarter use of existing ones?

I do think we've made a lot of progress since then. Almost every lab I talk to now is either already measuring ultra-short- and short-chain PFAS, or actively gearing up to do so – and that's helping close the gap quite a bit. Many samples contain significant amounts of trifluoroacetic acid (TFA), which used to be largely overlooked. In some extractable organofluorine (EOF) measurements, TFA could even be lost, so it wasn't always captured consistently. Now that researchers are focusing specifically on TFA and other ultra-short compounds, that's definitely reducing the unidentified fraction.

The adoption of GC-high-resolution methods is also progressing – more slowly, but steadily – and that will help too. My sense is that a lot of the unidentified fraction in commercial products, and potentially in human tissues, could be compounds that simply aren't amenable to LC-ESI, so we just haven't been seeing them. As labs expand into GC-EI/CI and GC-APCI, and develop methods for highly soluble compounds using different chromatographic approaches, we're starting to detect more of them.

^{19}F NMR has also come a long way. It used to be seen mostly as a way to confirm that organofluorine was present, without providing much structural detail. Now, you can get some structural information, and using NMR complementarily alongside other methods is becoming increasingly common.

Overall, I think we've advanced a great deal – not necessarily by inventing brand-new tools, but by expanding how and where we apply the ones we already have.

How do factors like bioaccumulation fit into the bigger picture of PFAS risk assessment?

Our work tends to focus on everything that happens before toxicity – essentially, everything leading up to the point where a compound reaches its target concentration and activates a receptor. Beyond that, I usually collaborate with toxicologists, because things get much more complex. But all the steps leading up to that point are equally important – and often overlooked.

For instance, when people run in vitro toxicity assays, they might try to mimic real-world mixtures – which is good, because we're never exposed to just a single PFAS compound. We're always exposed to mixtures. But what those experiments often miss is that what cells actually "see" isn't the same as what's in the water or exposure medium. Cells are exposed to the compounds that persist long enough to bioaccumulate – those with long biological half-lives. So, over time, the molar ratios your cells experience are very different from those in the original mixture.

A lot of our research focuses on that question: if you're exposed to a certain mixture, what actually ends up in your cells, and how is it distributed throughout the body? That's the toxicokinetics side of things.

Bioaccumulation has always been a core part of risk assessment, but with PFAS it's far more complicated. People who specialize in PFAS understand this, but it's still gaining traction more broadly in the risk assessment community. Traditional risk models assume that chemicals accumulate in fatty tissues – in the lipids – and that their distribution is governed by hydrophobicity and affinity for organic carbon. PFAS don't behave that way.

They interact with transporter proteins, bind to phospholipids, and engage in more polar interactions, so the classic POPs (persistent organic pollutants) models don't really apply. Because of that, we need new models that capture these unique behaviors – especially for assessing long-term, low-level chronic exposures like those from drinking water. Otherwise, we're not accurately representing what the body is actually experiencing over time.

How close are we to understanding what all these PFAS are doing to us?

I'd say we have a good foundation – but there's still a long way to go.

We do have strong epidemiological studies showing clear effects from certain PFAS, particularly the well-studied compounds like PFOS and PFOA. These are also the ones most frequently detected and often found at the highest levels in human blood and other tissues. In contaminated communities, where most of the measured organofluorine can be explained by these known compounds, a lot of the observed health effects and risk appear to be driven by them.

So, in that sense, we do have solid information – certainly enough to justify stronger regulatory action than we're currently seeing. But many questions remain, especially around mechanisms and how these compounds are distributed in the body.

One major focus of my work is precursors – compounds that

can transform into perfluoroalkyl acids but may have very different potencies or behaviors. If you're exposed to neutral, volatile PFAS in cosmetics or consumer products, they can degrade into terminal perfluoroalkyl acids – but where does that transformation happen? On your skin? In your skin? In the liver? In the gut, before they enter your bloodstream? Understanding where and how those conversions occur is crucial – as is understanding the difference between being exposed to a poorly characterized precursor versus its well-studied breakdown product.

Another major area of uncertainty involves the short-chain and ultra-short-chain compounds. Much of my work takes a bioaccumulation-directed prioritization approach – the idea that compounds persisting in the body will reach higher concentrations in cells than those that are rapidly excreted. But even if short, highly soluble PFAS don't bioaccumulate, continuous exposure still matters. If you drink the same contaminated water every day, you're being constantly re-exposed to them.

The challenge is that most toxicology assays – particularly short-term exposure models – aren't designed to address chronic, low-level exposure to soluble compounds. We need much more research targeting those long-term, everyday exposures. That means rethinking experimental design and moving beyond some traditional approaches. It will take time, but it's essential if we want to truly understand the risks posed by the full range of PFAS.

From an analytical standpoint, how effective are current remediation approaches – and what are their limits?

Yes – I've done some work evaluating remediation technologies, and I expect to do more in the future. When I was working with Chris Higgins, and later during my three years at Stony Brook – before joining Carnegie Mellon – I was in an engineering department where a lot of PFAS treatment research was taking place.

Early on, when I began collaborating with engineers on PFAS treatment projects, I often found myself saying: "Just because PFOS is going down doesn't mean this is a good treatment technique." That mindset seems to have caught on now. These days, many researchers are using untargeted methods, measuring total organic fluorine, or monitoring fluoride release as part of their treatment evaluations – which is really encouraging to see.

Much of the early remediation work I saw (and sometimes contributed to) simply transformed long-chain PFAS into short-chain ones. That can make it look as though treatment is working – because the regulated compounds disappear – but in reality, you're often just creating shorter chains that are harder to remove and may eventually be regulated themselves. We did a lot to highlight that issue, and I'd like to continue exploring it, especially from the non-targeted analytical side.

I often talk with collaborators about how to confirm mineralization – which is now seen as the "holy grail" of remediation: actually breaking PFAS down completely, releasing fluoride rather than generating TFA or other persistent by-products.

Overall, remediation is important – and we should be using the most advanced techniques available, especially for drinking water treatment. That said, I think the real solution is avoiding PFAS altogether. For the newer exposure pathways I'm studying – where PFAS exposure comes directly from products – if you're still using PFAS, you're still being exposed. There's no way to "treat" that exposure.

And for contamination that's already out there – in oceans,

Looking at IMS data with postdoc Dr. Yanan Chen

sediments, even stored in the Arctic – there's no realistic way to clean it up at scale. We can treat drinking water before people consume it, but once PFAS are in fish, for example, it's too late. They live in contaminated water. You can't treat all the water, and once PFAS accumulate in their tissues, there's no way to remove them. We can test and measure, but if we want to eat fish, there's simply no method to make them PFAS-free.

So remediation has limits – and it's important to keep that in mind when communicating with the media. I worry when I see headlines claiming, "PFAS are no longer forever – we can break them down." Usually, that means a few PFCAs can be degraded under very specific lab conditions, using highly specialized processes. You might be able to apply those techniques in a pump-and-treat system or a drinking water plant – but they're still early-stage and don't solve the global problem.

I worry people will see those headlines and think, "Oh, the problem is solved – we can keep using them." And some industries would be very happy for that perception to spread. But that mindset doesn't solve anything.

We need to stop using organofluorines in products that don't absolutely need them. Yes, there are essential pharmaceuticals and certain safety-critical materials where PFAS are probably still necessary – but for many other uses, I have faith in the ingenuity of synthetic chemists. They're already finding ways to achieve those useful properties without adding a fluorinated methyl group or a perfluoroalkyl chain to everything.

Where can the next generation of analytical chemists make the biggest impact on the PFAS problem?

Definitely on non-targeted analysis. Get really solid training in high-resolution mass spectrometry – which is still something of an art – and, ideally, in machine learning and big data analysis as well. We need more people who can bridge those two worlds, because there still aren't many researchers fluent in both. That combination could help us prioritize what to investigate, rather than getting lost in the sea of possibilities.

Right now, even in my own group, we sometimes get stuck in "analysis paralysis" – there are so many tools and workflows for non-target analysis that it can be dizzying. You start down one path, then pivot to another, and it's easy to lose sight of the core question. Having more researchers who can design better prioritization and filtering strategies would be incredibly valuable.

For those working on PFAS analysis, I'd also say: don't limit yourself to one sample introduction or ionization technique. The field often defaults to ESI and C18 LC columns, because those were ideal for PFOS and PFOA when we first realized they were a problem. But they're not necessarily ideal for all PFAS. Gain experience with a range of tools – GC-APCI, GC-EI, and alternative chromatographies – especially for detecting ultra-soluble compounds that conventional methods might miss. That kind of versatility will be essential.

Another point I emphasize with students is that there's a real need for more master's-level training in analytical chemistry. Many of the undergraduates in my lab want to work in industry doing PFAS analysis. They often find that a bachelor's degree isn't enough, but a PhD feels like overkill. In reality, a master's can open many doors – especially since a lot of instrument companies hire PhDs for roles where a master's would be perfectly suited. For students aiming for analytical or industry-focused careers, that's a great path to consider.

And finally, in all my classes and training, I tell students: make sure your results make sense. It sounds simple, but it's easy to lose sight of in non-target PFAS work. If you think you've found an ultra-short-chain compound in dolphin blubber, stop and ask – does that make sense? Could it be something else? Bring what we already know about compound properties into your interpretation. That kind of critical reasoning is something students often aren't explicitly trained in – but it's absolutely essential for doing good non-target analysis.

What key message would you like analytical scientists – especially those outside the PFAS field – to take away?

The main message I'd want to share with analytical scientists – especially those who aren't deeply involved in PFAS research and are simply looking for clear answers about contamination – is this: if you're not performing any kind of total organofluorine analysis, you're not seeing the full picture.

Correlation isn't causation, and PFOS and PFOA are not the whole story. We need to stay aware that without using a variety of ionization techniques, sample introduction methods, and broader analytical approaches, we're only observing a narrow slice of the PFAS universe.

And something people often forget: not all PFAS are immutable. Most PFAS are precursors – compounds that can transform into perfluoroalkyl acids. While the end products may be persistent, the majority of the PFAS universe consists of transformable compounds. Transformation processes really matter for PFAS – they're often overlooked, but they're critical to understanding the problem in its entirety.

Spotlight On...

Activated-carbon delay column minimizing PFAS background in LC/MS.

Delay Column for PFAS improves LC/MS analysis of per- and polyfluoroalkyl substances by suppressing background signals that originate from the mobile phase and LC system hardware. The column is packed with high-purity activated carbon, which strongly retains PFAS-type contaminants introduced from solvents, tubing, and valves. Because these background species are retained and their elution is delayed, they no longer coelute with the target PFAS window – reducing baseline drift and ion-source contamination, and improving limits of quantitation and data confidence.

How it works. Placed upstream of the injector or before the analytical column, the delay column acts as a trap. Mobile-phase-borne PFAS are held back on the activated carbon and elute later than the analytical window of interest. This minimizes false positives and mitigates ghost peaks that can compromise method robustness.

For laboratories monitoring PFAS in environmental waters, food contact materials, or other matrices, the Delay Column for PFAS offers a simple, robust way to stabilize baselines and protect data quality without altering existing LC/MS methods.

GET MORE DETAILS ON OUR WEBSITE

Confronting the Messy Reality of PFAS Regulations

David Megson calls for joined-up thinking, smarter analysis, and stronger partnerships between academia, industry, and government

David Megson first got involved with PFAS when he was working in North America as a postdoc. He realized that they were about eight to ten years ahead of where his native UK was. "They'd already recognized it as a major problem and were actively trying to tackle it – there was a real surge in developing analytical techniques," he says.

When he came back to the UK around 10 years ago, he was surprised by how big the gap was. "There just wasn't the same level of awareness or urgency. I went from a place where PFAS were treated as a top priority to somewhere they were barely on the radar."

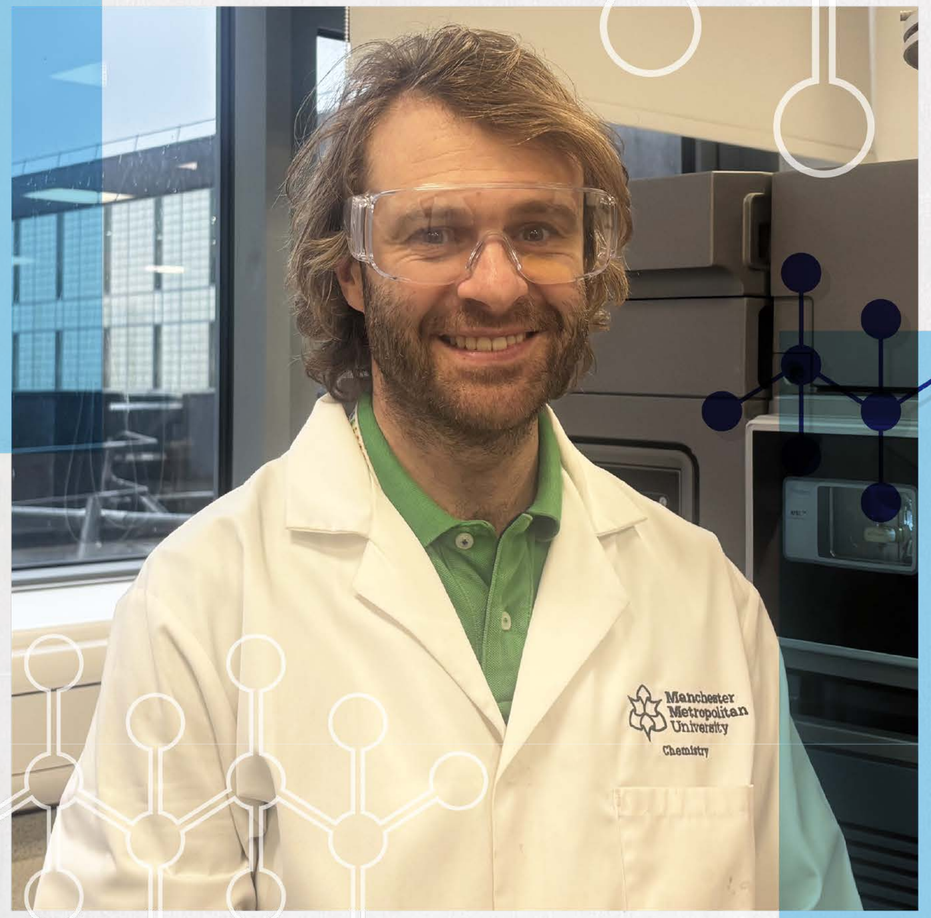
This led Megson, now Associate Professor of Environmental Chemistry at Manchester Metropolitan University, UK, to focus on raising the profile of PFAS in the UK – through media outreach and also by supporting people from within the community and helping them upskill. He helped to organize a series of network meetings and open "ask me anything" sessions with experts, to build understanding and spark dialogue. "That really helped people start to get their heads around how we could regulate and manage PFAS more effectively here in the UK," he says.

Since then, and largely due to coverage in the media, PFAS has become a key priority for government agencies. "It can feel like an article comes out highlighting a specific issue, and suddenly the relevant agencies jump into action," says Megson. "For example, when there was coverage about PFAS in Cambridgeshire drinking water, the UK Drinking Water Inspectorate (DWI) quickly mobilized, putting in resources and coming up with new guidance for water. Then another story might focus on food, and suddenly the Food Standards Agency, Fera, and DEFRA are responding with their own guidance – often with different PFAS targets and methods. I know these agencies are constantly working and reviewing guidance on this complex evolving issue, but hopefully the media pieces have provided them with justification and support to do the work they want to do"

The result, however, is a fractured regulatory landscape. "Depending on what you're sampling, everyone is looking for different PFAS, using different lists, different methods, and different priorities."

He believes the time is right for the UK – and for governments around the world – to take a more joined-up approach – to align how we assess risk, monitor contamination, and conduct routine testing. "Research shows that even if you're measuring PFAS A, B, C, and D, there are thousands of others out there. So we have to ask: are we even looking at the right ones? Are we collecting the right data to truly understand the risk to people and the environment?"

Here, in the fourth installment of our PFAS: New Frontiers, Emerging Solutions series, David Megson, Associate Professor of Environmental Chemistry at Manchester Metropolitan University, UK, reflects on the fractured state of PFAS regulation, the rise of "regrettable substitutions," and how analytical chemistry can help build the evidence base for meaningful reform.



"Non-targeted work is too expensive and complex to do routinely on every single sample, but as a check – to make sure we're not overlooking important PFAS – it's incredibly valuable."

With so many PFAS – estimates range from thousands to millions – and only a small number clearly linked to toxicity, how are regulators even beginning to navigate that landscape?
Honestly, they must be tearing their hair out. There was a paper by Buck et al., in 2021, that listed 256 commercially relevant PFAS. Then the OECD came out with about 4,700. The US EPA databases now list over 10,000. And then there's the Szymanski et al 2023 paper suggesting there could be up to seven million potential PFAS if you include anything with CF_2 or CF_3 groups. So how on earth do you regulate that? It's a nightmare.

Within our lab we've been trying to chip away at the problem by asking: within this entire theoretical universe of PFAS, which ones are actually turning up in the environment when we do non-targeted analysis? And so far, we've found thousands. We identified 382 unique structural classes – which probably corresponds to about 3,000 to 4,000 individual PFAS that have actually been detected in the environment.

But, as you said, that's only half the challenge. Yes, we can detect them – but their toxicities vary enormously. And assessing toxicity properly requires a huge number of different tests across different endpoints. The most reliable data often comes from animal studies, which are expensive, time-consuming, and ethically complicated. So there's massive uncertainty on that side as well.

At the moment, there are two polarized schools of thought. One says: the carbon-fluorine bond is so strong that these chemicals will persist for decades. We can't test them all, so let's take a conservative approach – assume they're risky until proven otherwise. The other – currently used approach, which is more favorable to PFAS manufacturers and users – argues: we don't have the data to prove they're toxic and persistent, so it's fine to keep using them until evidence shows us otherwise.

As we slowly identify that an individual PFAS poses a significant risk we are now starting to see a "regrettable substitution" cycle: one PFAS is used widely, and over ten or fifteen years, enough evidence builds up to show it's persistent and toxic, so it gets banned. Industry then switches to a slightly more degradable replacement – but that just breaks down into two new PFAS, both persistent and toxic. Then we ban those and move to the next ones.

It's a repeating ten-year loop of replacing one harmful compound with another. That's why what's happening in Europe is so interesting – they're trying to take the more conservative approach of banning all PFAS as a single class. It's a huge shift, and it really highlights just how differently the problem is being approached around the world.

PFAS are incredibly useful materials, often without clear replacements. How do you think we should balance the benefits with the risks?
For the public, the perception tends to be that "chemicals are bad" – when in reality, we're made of chemicals, we drink chemicals, and they're essential to modern life. PFAS have a terrible reputation at the moment, but the truth is, they're an extraordinary group of chemicals. They have so many valuable properties; that's why they became so widespread in the first place.

The issue isn't the chemistry itself – it's how we've used these substances: irresponsibly, without adequate controls, and without any kind of circular economy. I genuinely think there's a version of the world where PFAS can coexist with us – if we use them far more responsibly, and only in essential applications.

But right now, they're used in countless products where they're not needed, and often where safer alternatives already exist.

If you were advising someone in industry, what would you tell them about the next five years of PFAS regulation and testing?
If it's a marginal call – and you've got the option to move away from PFAS – take it. Get out of PFAS.

I remember going to a Royal Society of Chemistry meeting of the Fluorine Interest Group. It was full of people who work with fluorine to produce useful chemicals for our everyday lives, so I felt like the awkward voice in the room saying, "This is really bad." A lot of them said, "Well, we use CF_3 because it works well – it's what we've always done."

But when you actually look at the data, in many cases it may be possible to replace CF_3 with a single fluorine atom and it performs just as well. It's often just habit that's keeping people tied to CF_3 chemistry. So there's definitely scope for companies to make changes.

Of course, in the pharmaceutical world, it's much harder. If a drug is already on the market, you can't just swap out a CF_3 for an F without revalidating the whole drug – which is hugely expensive, time-consuming, and comes with no guarantee it'll work the same way. But going forward, whenever there's a marginal design decision, my advice would be: get rid of the CF_3 and CF_2 groups. Focus on PFAS alternatives.

And I think that's where government funding could really help – to drive the R&D needed to develop those alternatives. It's a great opportunity for industry and academia to work together. With just a bit of targeted support, everyone could win.

What promising analytical approaches are emerging right now?
Several, actually. There's a lot of exciting work happening in this space.

One is combustion ion chromatography, where you essentially roast the sample to break down all the compounds, release the fluorine, and then measure the fluoride ions. If you subtract the inorganic fluorine naturally present in the sample, you get a solid worst-case estimate of "total fluorine."

Another is the TOP assay – the *Total Oxidizable Precursor* method – which chemically converts PFAS into their most stable (and often most toxic) forms. From a risk-assessment point of view, that's really useful because it captures the nastier PFAS within one total number.

So we now have a few "total" approaches that can be used alongside targeted ones. The framework I've been advocating for is simple. First, do your targeted analysis on the 40 or so PFAS we routinely measure. At the same time, run one of the total methods on one composite sample – it doesn't matter which, just pick one and start using it. Then compare your results.

If your targeted total PFAS matches the total fluorine number – great, your targeted method is capturing the key compounds. But if there's a big gap between the two, that's your signal to bring in non-targeted analysis using high-resolution mass spectrometry to identify what's missing. Once you've found those new compounds, you can add them into your targeted screen.

Non-targeted work is too expensive and complex to do routinely on every single sample, but as a check – to make sure we're not overlooking important PFAS – it's incredibly valuable.

Who needs to be driving that change – the labs doing the analysis or the companies commissioning it?
I think the key point is that labs respond to what their customers ask for – so ultimately, it has to come from the customers. The labs have already shown what they can do when there's a clear demand. When the UK DWI suddenly said, "we now need to start testing for these 47 PFAS," they rose to the challenge. Chemically, those PFAS are very different from each other, so developing a single validated method that could cover that entire range was technically tough – but they nailed it in less than a year. That was seriously impressive.

Now we're starting to see more "total" methods coming into use, and even some labs beginning to offer non-targeted analysis. The tools are there – they exist in academia and are starting to move into the commercial lab space – but only if customers demand them.

What we need is a bit of a regulatory nudge and more awareness, so people know these techniques exist and start asking for them. The only catch is: if you do find a brand-new PFAS at high concentrations, what does that *actually* mean? We often don't have the toxicological data to say whether it's a problem. So understandably, some people hesitate to look for things they're not sure how to interpret.

That's why we need toxicologists and chemists working hand

"We now have some really strong analytical tools to help untangle this complex issue. We can identify key sources and estimate their contribution to environmental PFAS levels."

in hand. The toxicologists are brilliant – they can do this – it's just about connecting all the right people so we can finally start solving the problem together.

Are there any efforts to connect detection and toxicology data in a more coordinated way?
It'd be lovely, wouldn't it? But I haven't really seen much happening yet in the UK. There was a NERC call – that's the UK's Natural Environment Research Council – specifically focused on PFAS, but the funding was tiny, nowhere near enough to scratch the surface of such a huge challenge.

To do it properly, we'd need real investment and a joined-up approach: something where industry contributes funding, labs and academia match-fund, and government acts as the central coordinator to pull it all together. It's not impossible – the expertise is out there – but it needs that initial, coordinated push to get off the ground.

It's easy from the outside to paint "big industry" as the villain, but I like to think most people working in those roles don't want to poison the world. They do want to find safer alternatives and protect people – and when I've spoken to them, that's genuinely the sense I get. They're actively investigating replacements.

But at the end of the day, if the regulations say, "You can do this," and the person making that final call is driven by profit, there's really only one direction things will go – until the rules change. That's why we need both: a stronger stick of regulation to enforce change, and a carrot to encourage the development of safer alternatives. That's how we move things forward most effectively.

Looking ahead, what's the key to improving our understanding and management of PFAS contamination?
I think the main point concerns the power of non-targeted analysis. What we're finding is that targeted analysis is starting to let us down. It's great for capturing the general background of PFAS, so it's useful when there isn't a major issue – but PFAS contamination is actually very source-specific.

We've been doing quite a bit of environmental forensics work to pin down techniques for identifying PFAS sources in the UK, and that's been incredibly powerful. Using non-targeted methods, we can detect PFAS that are unique to certain processes or manufacturers. We can also use the chemical "fingerprint" – looking at the relative ratios of individual PFAS within classes, and within the overall profile – to trace contamination back to its source.

So we now have some really strong analytical tools to help untangle this complex issue. We can identify key sources and estimate their contribution to environmental PFAS levels. Where we're still falling short is on the joined-up regulation and the toxicological testing needed to prove whether those chemicals – individually and, crucially, as mixtures – are causing harm. That's where the real challenge lies.

Finally, what's your key message to readers about the path forward?
I think it's important to stress that we already have excellent analytical tools to monitor PFAS effectively. Once the regulation catches up – and it will – the science is ready to support it. The techniques exist to help us measure, manage, and ultimately make better decisions about PFAS. It's just about joining the dots between policy, toxicology, and analysis to actually make it happen.

Spotlight On...

The FM4 Air Sampler collects and elutes atmospheric PFAS for GC-MS/MS and LC-MS/MS analysis.

This application elutes atmospheric ionic and neutral PFAS in solvent after solid collection and contains information on analysis by GC-MS/MS and LC-MS/MS.

The Air Sampler for PFAS FM4 is the world's first innovative portable sampler that enables simultaneous collection and analysis of atmospheric particle and gas-type PFAS.

FM4 consists of an impactor and three types of collectors to efficiently collect PFAS present in particle and gas types. Pfas collected in each collector can be eluted with an organic solvent to comprehensively analyze PFAS in the atmosphere using GC-MS/MS and LC-MS/MS.

A newly developed newly developed activated carbon adsorbent (GAIAC) is used as a gas-type collector. Conventional activated carbon has problems such as complex pores and adsorption, but insufficient elution. GAIAC is an innovative adsorbent made of synthetic resin fibers and optimizes pores and surface activity, enabling pfas collection and elution.

GET MORE DETAILS ON OUR WEBSITE

Portable Sensors: The Next Generation of PFAS Detection

Silvana Andreescu on the urgent need for low-cost, field-deployable PFAS sensors

Much is known about the exceptional stability and resistance to degradation of PFAS compounds. But when it comes to detection – argues Silvana Andreescu, Professor of Bioanalytical Chemistry at Clarkson University, USA – the field is still playing catch-up.

Researchers are dealing with an enormous number of PFAS compounds – thousands, with different chain lengths, sizes, and functional groups – which makes it incredibly difficult to develop selective detection methods. "Often, we can only target one compound at a time, or maybe a small subclass," she says. "Detecting degradation products is even harder, because there are no analytical standards available for many of them, even using conventional techniques."

Then there's the issue of ultra-low – parts per trillion – detection limits. "The established EPA methods using LC-MS/MS can reach those limits accurately, but they require extensive sample preparation and sophisticated instrumentation – resources that not every lab has access to," says Andreescu. "And even then, those LC-MS/MS methods only measure a small fraction of the PFAS universe."

On the regulatory and implementation side, most detection is still centralized. "There simply aren't enough accredited labs to handle the demand for PFAS monitoring. The analyses themselves are expensive and slow – turnaround times can be weeks or even months, with costs ranging from roughly $200 per water sample to $600 or $700 for biological samples."

So, given the scale of monitoring required – especially for regulatory enforcement – that combination of cost, complexity, and limited capacity becomes a major bottleneck. As a result, there is a growing movement – spearheaded by researchers like Andreescu – to take PFAS detection out of the lab and into the field.

In this interview, Andreescu discusses how advances in portable sensing technology – from optical and electrochemical sensing to new functional materials designed for molecular recognition – could complement gold-standard LC-MS-based approaches and expand global monitoring capacity.

Given the high cost and slow turnaround of centralized lab testing, is there growing interest in field-based or in situ approaches?
Yes, absolutely – this is becoming a very active area of research. If you look at the literature from the past five years, there's been a clear surge in new analytical methods and sensor technologies for PFAS detection. The interest is being driven by several factors: the high cost of current lab-based methods, increasingly strict regulatory limits that demand broader monitoring, and, of course, scientific curiosity – because PFAS present such a fascinating analytical challenge.

If we can develop reliable, low-cost, field-deployable sensors, that would be a real breakthrough. They could make large-scale monitoring feasible, reduce the cost and workload for centralized labs, and even be used in real time to optimize remediation – for example, by measuring PFAS levels before and after treatment directly in the field.

There's a huge practical need and a clear market opportunity here, which is why so much momentum is building around field-based sensing right now.

How do these newer sensing approaches compare with traditional techniques in terms of sensitivity and performance?
There's no question that LC-MS/MS remains the gold standard. It's highly reliable and can distinguish and quantify many PFAS compounds – at least those currently on regulatory lists. But it's also slow, expensive, and resource-intensive. You need specialized personnel and facilities, and not every analytical lab has that capability.

By contrast, the new generation of low-cost sensors can't yet match LC-MS/MS for accuracy, but they're improving fast. In recent years, we've seen promising developments in portable, lower-cost optical, fluorescence, and electrochemical devices. Some of these are already achieving regulatory limits in the parts-per-trillion range – occasionally even sub-ppt – and showing good selectivity for individual PFAS such as PFOA or PFOS, particularly when materials with molecular recognition are used.

That said, many of these devices still detect at higher concentrations, well above EPA limits, and often need pre-concentration steps. Reliability is another hurdle. Most are still at the proof-of-concept stage and haven't been widely tested on real-world samples, so they're still maturing in terms of robustness and consistency.

And there's a deeper question too: do we really need a sensor for every single PFAS? That's probably impossible. A more practical goal is to develop screening-type sensors – tools that can rapidly scan thousands of samples and flag a smaller subset for confirmatory LC-MS/MS analysis. I think that kind of tiered approach offers one of the most promising paths forward for PFAS detection.

What sensing strategies or technologies do you see as most promising – and what makes them stand out?
In terms of deployability and performance, most current PFAS sensing strategies fall into three main categories: spectroscopic and electrochemical approaches. On the optical side, we're seeing fluorescence-based and Surface-enhanced Raman spectroscopy (SERS) ; on the electrochemical side, a variety of voltammetric and impedance-based devices. The big advantage of these platforms is that they rely on low-cost, widely available instruments – things like UV-Vis spectrometers, fluorimeters, basic electrochemical readers, or Raman instruments. If we can develop reliable PFAS sensing methods using these tools, they could be implemented in almost any lab with fairly standard equipment.

Electrochemical methods tend to be more sensitive than optical ones, and most of the platforms that have achieved low parts-per-trillion detection limits fall into this category. These are, in my view, the closest to being truly field-deployable while still maintaining the required sensitivity.

Another major trend is the use of advanced functional materials to improve selectivity – giving sensors molecular recognition capabilities for specific PFAS. Molecularly imprinted polymers (MIPs) are a classic example, and metal-organic frameworks (MOFs) have also shown strong potential for PFAS capture. In some cases, researchers are combining these materials into hybrids that enhance both binding and signal response.

Most proof-of-concept sensors are still focused on individual PFAS such as PFOA, PFOS, or GenX, or they respond more broadly to carbon-fluorine bonds across classes. But as building blocks, these material-enhanced optical and electrochemical platforms represent some of the most promising directions for future PFAS sensing.

Could you tell me a bit about your own work on PFAS sensing?
My background is in developing sensors and sensing systems – I've been doing this for about 25 years – and over that time my group has created a range of platforms for different analytes. I first became interested in PFAS about five years ago, when the challenge was put to me very directly: could we design sensors capable of detecting PFAS at parts-per-trillion levels, even in complex matrices like drinking water, groundwater, or wastewater?

That became our starting point. We evaluated the optical and electrochemical materials already in our lab – some of which showed affinity for fluorinated species – and began adapting them specifically for PFAS detection. From the outset, we defined a set of design goals: high sensitivity (down to EPA ppt-level limits), adaptability to standard laboratory instruments, cost-effectiveness (ideally just a few dollars per probe), simplicity of operation, and scalability for large-scale production. We also wanted the platform to work either for specific compounds such as PFOS and PFOA, or for broader screening of total or subclass PFAS.

Because there are no natural receptors or antibodies for PFAS, we couldn't simply create a lateral flow test – which made the project more complex. But after about five years of work, including contributions from three PhD students, we now have two functioning sensor platforms, one of which looks particularly promising.

Our main platform is an electrode-based sensor that can detect PFOA and PFOS at or below the EPA's ppt limits. All reagents

"Our main platform is an electrode-based sensor that can detect PFOA and PFOS at or below the EPA's ppt limits."

are built directly into the probe, so the workflow is remarkably simple: incubate the sample for a few minutes, then measure the electrochemical signal. No additional reagents are required beyond buffer and sample – it operates almost like a glucose meter.

We've since tested real-world samples, including industrial wastewater, and compared the results with LC-MS/MS. While it doesn't quite match that gold-standard precision, the results showed about 85 percent agreement – which is very encouraging for a portable, field-deployable platform that's still being refined.

Looking ahead, what are the biggest barriers to wider adoption of PFAS sensing technologies?

Honestly, it's a bit of everything. Technically, we've demonstrated that our sensors can reach parts-per-trillion detection limits, but so far that's been at the bench scale, on a relatively small number of samples. The next major step is to prove they can perform consistently across hundreds, or even thousands of real-world samples from environmental and industrial settings.

That means collaborating closely with field practitioners to understand what kinds of samples and matrices they encounter, what typical PFAS mixtures and concentration ranges look like, and what potential interferences might occur. We've been driven by scientific curiosity so far, but moving beyond the lab really requires partnerships with industry, utilities, and local communities – and we've already begun building those connections, particularly with drinking water providers.

On the regulatory side, the challenge is validation. LC-MS/MS remains the accepted standard, so any new sensor platform has to go through formal performance benchmarking in multi-lab studies and gain endorsement from the wider community – not just from academic groups.

That's where the field is right now. There are many exciting proof-of-concept sensors being published, but only a few will advance to real-world deployment. The ones that succeed will be those that bridge that gap – demonstrating robust, reproducible performance outside the lab, at scale.

Are you optimistic about the prospect of pushing PFAS sensors from the lab into real-world use – in the near future?

From our experience and review of the PFAS sensing literature, it's clear this is a difficult challenge – analytically, technologically, and from a regulatory perspective. But there's a tremendous amount of work happening right now.

I'm optimistic that within the next year or two, we'll see some of these technologies move beyond the lab – probably starting with PFOA and PFOS, where regulatory attention is strongest. The critical next step is interlaboratory validation with real-world samples – and that's something several of us are actively working on right now.

For real-world use, we'll need stronger engagement from industry and local communities. As academics, we can push the science forward, but scaling and deploying these tools requires true collaboration – people on the ground who can help validate and implement them in practice. That's the step that will really make the difference.

Spotlight On...

Stacked SPE cleanup for high-recovery PFAS analysis.

InertSep stacked SPE cartridges for PFAS analysis combine WAX FF and GCB sorbents in a single, ready-to-use cartridge. This stacked design streamlines sample preparation by integrating PFAS retention and matrix cleanup into one workflow.

The WAX FF layer is designed for PFAS extraction, while the graphitized carbon black layer provides powerful cleanup of complex matrices. Together, they help reduce interferences and support high recovery from challenging sample types, including aqueous, soil, food, and other environmental or matrix-rich samples.

Available as InertSep WAX FF/GCB and InertSep GCB/ WAX FF, the cartridges are well suited for EPA Method 1633 and related PFAS workflows where reproducible extraction, effective cleanup, and lower background are essential.

GET MORE DETAILS ON OUR WEBSITE