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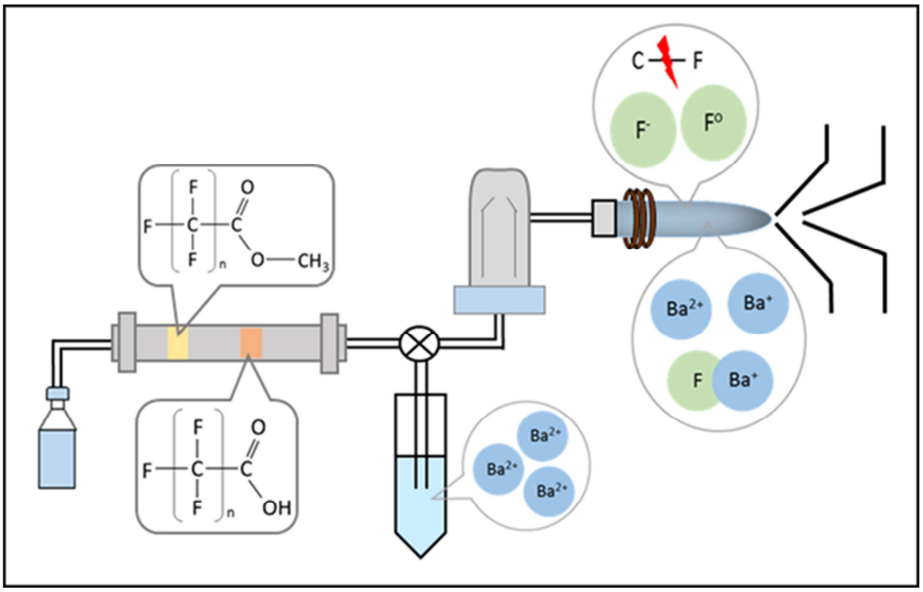

Perfluorinated carboxylic acids are separated and quantified by using a reverse phase liquid chromatography coupled to ICPMS. The fluorine specific detection was made possible by forming BaF^+ in the argon plasma.

Novel non-targeted analysis of perfluorinated compounds using fluorine-specific detection regardless of their ionisability (HPLC-ICPMS/MS-ESI-MS)

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ABSTRACT

Although perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA) have been phased out, there is a plethora of per- or polyfluoroalkyl substances (PFAS) generated and only a small number of these compounds are currently being monitored in environmental and biological sample using molecular mass spectrometry (MS). Total fluorine determination has revealed that a substantial amount of fluorinated organic compounds has not been identified. Due to the small mass deficiency of fluorine, it is not an easy task to screen successfully all fluorinated compounds including those which are not easy ionisable, hence a novel fluorine-specific detector is needed. Here, inductively-coupled plasma mass spectrometry (ICPMS) was used for the first time for the detection of PFAS, by using the novel approach to transfer F^- into a detectable $[BaF]^+$ in the argon plasma. A reverse phase-high performance liquid chromatography (RP-HPLC) method was developed and then online coupled to ICPMS/MS for the fluorine-specific detection and simultaneously to electrospray MS (ESI-MS) to separate perfluorinated carboxylic acids (PFCA) and perfluorooctanesulfonic acid (PFOS). The calibration was linear and was element-specific with detection limits of 0.49 mg F L^{-1} under gradient elution method. As a proof of concept, PFCA standards in methanol were not fully neutralised to force the esterification and those solutions were measured using HPLC-ICPMS/MS-ESI-MS. The methyl esters were not detectable by ESI-MS but by ICPMS/MS. This illustrates that the undetectable fluorine-containing compounds were detected and quantified by the element-specific detection of ICPMS/MS. The analysis of spiked river water at a sub-ppb level gave acceptable recovery using a SPE-based preconcentration method. Since ICPMS/MS method is element-specific detection, all non-fluorinated compounds interfering in ESI-MS were eliminated. Hence, HPLC-ICPMS/MS can be used as a non-targeted method of fluorinated compounds which may help the identification of novel fluorinated compounds in environmental and biological samples and helps with mining the ESI-MS data.

Keywords: non-target method, ICPMS/MS, polyatomic ion $[BaF]^+$, perfluoroalkyl substances

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1. Introduction

Fluorinated organic compounds are widely being used in various applications especially as a surfactant for commercial products such as carpet, textiles, cookware, packaging, personal care products and firefighting foams [1–4]. Not only the C-F bond is one of the strongest in organic chemistry, it is also very persistent in the environment especially perfluoroalkyl carboxylic acid (PFCA) and perfluoroalkane sulfonic acid (PFSA). Both are among the group of per- or polyfluoroalkyl substances (PFAS) which received more attention recently due to their ubiquitous presence in the environment. Some studies have revealed that PFSA and long chain PFCA are toxic and bioaccumulate in human and animal [5,6]. In 2009, perfluorooctanesulfonic acid (PFOS) has been listed as a persistent organic pollutant (POP) in Annex B, Stockholm Convention resulting in global restriction of its production and use [7].

Industries have developed different fluorinated precursors and shifted their formulation of fluorinated polymers to the new chemical structure. In addition, there are still sources of PFOS and other PFCAs resulting from oxidation and reduction process of unknown precursors [8]. These lead to the production of other so far unidentified fluorinated compounds, which in some cases can make up almost 60 to 90% of the total organofluorines in environmental and biological samples [5,9,10]. For example, Yamashita and co-workers demonstrated that animals on the bottom of the food chain contain at least one order of magnitude higher concentration of organofluorines which could not be detected by the targeted analysis usually used (HPLC-ESI-MS/MS) [10]. Either those organofluorines were not ionisable by APCI or ESI and only accessible by GC-MS methods, or simply no standards were available for their identification and quantification. Since the mass defect of fluorine is rather small (-0.0016 Da) and fluorine is mono-isotopic, an algorithm for mining the mass spectra is difficult especially if the number of fluorine atoms in the molecule is unknown.

A plethora of analytical methods are available for the detection of organofluorines, however what missing is a fluorine-specific method, which is capable to detect possible novel organofluorines without having standards available. ICPMS is the ideal detector for non-targeted analysis of elemental compounds since it destroys all bonds including the most stable bond such as C-F [11]. Coupling HPLC to ICPMS/MS for non-targeted elemental analysis has been used for more than a decade to discover unknown elemental compounds such as the new class of arsenolipids [12]. However, fluorine cannot be directly detected by ICPMS mainly due to fluorine's high ionisation potential (17 eV), which prevents to produce significant amounts of F^+ in an argon plasma. This is important since all commercial ICPMS instruments today can only detect positive ions. Therefore, fluorine is impossible to determine directly in a commercial ICPMS. We have recently developed a method which made it possible to detect fluorine using ICPMS/MS by mixing barium solution with fluorine-containing solution in order to form the polyatomic ion of $[^{138}Ba^{19}F]^+$ [13].

In this study, we developed a new fluorine-specific method for the organic mode which could be used as a non-targeted method for organofluorines. As a proof of concept, RP-HPLC was directly coupled to ICPMS/MS and simultaneously to ESI-MS for the identification and quantification of a mixture of PFCA and their methyl esters as their degradation products. ICPMS/MS acted as a fluorine-specific detector and was used for quantification of the PFAS, while ESI-MS gave the molecular information of PFAS compounds separated by HPLC. To evaluate the method, real sample analysis on river water will be conducted.

2. Materials and methods

2.1. Materials and chemicals

Barium stock solution was prepared from barium nitrate, $BaNO_3$ salt (BDH, UK). Seven PFAS standards were examined in this study including perfluorohexanoic acid (PFHxA) (Sigma-Aldrich, Switzerland), perfluoroheptanoic acid (PFHpA) (Sigma-Aldrich, Rusia), perfluorooctanoic acid (PFOA), perfluorononanoic acid (PFNA), perfluorodecanoic acid (PFDA) (Sigma-Aldrich, USA), perfluorooctanesulfonic acid (PFOS) (Wellington, Canada) and methyl perfluorooctanoate (Me-PFOA) (Alfa-Aesar, UK). Oasis WAX (6 cc, 150 mg, 30 µm) solid-phase extraction (SPE) were purchased from Waters, UK. HPLC grade of methanol and acetonitrile were from Honeywell Riedel-de Haen, Germany, ammonium acetate was from Sigma-Aldrich, Germany, formic acid from Fluka, USA and ammonium hydroxide solution from Sigma-Aldrich, UK. Deionised water (18 MΩ cm, Smart2Pure, Thermo Fisher Scientific) was used throughout the study.

2.2. Sample preparation

River water (River Don, Aberdeen, NE Scotland) sample was filtered with a glass filter (1.6 µm). Then, the water samples (deionised and river water) were spiked with two standards of PFHxA and PFOA in different concentrations. The extraction was performed using Oasis WAX as described in the literature [14]. The SPE cartridge was pre-conditioned with 4 mL 0.1% of ammonium hydroxide (NH_4OH) in methanol, followed by 4 mL of methanol and 4 mL of deionised water. Water samples (1000 mL for deionised water and 1220 mL for river water) were passed through the pre-conditioned cartridges. The cartridges were then rinsed with 4 mL of 25 mM ammonium acetate (NH_4Ac) at pH 4 and this fraction was discarded. The analytes were eluted with 4 mL of methanol and 4 mL of 0.1% NH_4OH/methanol. The sample bottles were rinsed with methanol and used for the elution of SPE cartridges. Finally, the extracts were concentrated under a gentle stream of nitrogen to 0.2 mL giving a pre-concentration factor of approximately 4-6000.

2.3. Online Speciation Method (HPLC-ICPMS/MS-ESIMS)

To study the capability of the ICPMS/MS hyphenated to HPLC, two different separation methods were performed using a reverse phase column (ACE Excel 3 C18-Amide, 100 mm x 3 mm x 5 µm) with (A) isocratic 70% methanol and (B) gradient of acetonitrile/water. The use of an organic solvent made it necessary to use the organic mode for the ICPMS/MS: narrow injector torch (1.5 mm), micromist nebuliser, platinum sampler cone, nickel skimmer cone and S-lens were used. Since the organic solvent is introduced to ICPMS/MS in this study, the optimisation of ICPMS/MS parameters in the organic mode was conducted for maximum sensitivity. The optimised ICPMS/MS parameters in the organic mode was shown in Table S1. Fluorine was detected as a polyatomic ion, $[BaF]^+$ at *m/z* 157. Ba has been chosen to form polyatomic ions with F due to its prominent result and better sensitivity compared to other elements. The mechanism of $[BaF]^+$ formation and analytical explanation of the method have been described elsewhere [13,15]. Briefly, organofluorines are atomised and fluorine is ionised to form F^- in the plasma. F^- reacts subsequently with Ba^{2+} ions to form BaF^+. Table 1 show the details of the instrumentation for both elution methods and the formation of $[BaF]^+$ involve the 50 mg Ba L^{-1} with fluorine concentration range 0.1-10 mg L^{-1}.

3. Results and discussion

3.1. Online HPLC-ICPMS/MS of PFCA compounds

A mixture of perfluoroalkyl carboxylic acids (PFCA) was fully separated in reverse phase column with two elution methods: (A) isocratic 70% methanol and (B) gradient water and acetonitrile. The chromatogram of each fluorine compounds was recorded by ICPMS/MS at *m/z* 157 through the formation of polyatomic ions, $[BaF]^+$ as has been described in previous work [13,15]. Under isocratic 70% methanol elution, C_6 until C_{10} of PFCA compounds were separated with the same fluorine-specific response as $[BaF]^+$ (Fig. 1A). The response of $[BaF]^+$ changes with increasing acetonitrile concentration in the plasma due to acetonitrile/water gradient which is illustrated in Fig. 1B. This is not surprising since the different amount of carbon has been shown to influence the sensitivity of elements which exhibit higher ionisation potential and tend to not fully ionised [16,17]. Due to that, the response factor of each fluorine compound depends on acetonitrile concentration and the same effect has also been observed for arsenic and sulphur [16,18].

By knowing the specific retention time of fluorine response factor, the correct response factor for each fluorine compounds could be determined. This could be achieved by injecting a blank while running the gradient elution program and the response of $[BaF]^+$ was monitored (Fig. 2A). Fig. 2B show the changes in sensitivity during the chromatographic run with the intensity of $[BaF]^+$ illustrated as the relative intensity and linked to the acetonitrile concentration. For further data analysis, each chromatogram was corrected by taking the intensity data and divides it with the relative intensity from the response curve (Fig. 2C and 2D).

As shown in Fig. 1B, 2A, 2B and 2C, the chromatogram baseline of the gradient condition decreased with increasing acetonitrile concentration. This observation contrary to the published studies [12,16,18]. This could be explained by the reaction between the oxide or hydroxide interference ions (e.g., $^{138}Ba^{18}O^{1}H^{+}$) with carbon in the plasma [17]. As has been discussed in the earlier studies, $[BaF]^+$ was interfered with barium hydroxide ions $[BaOH]^+$ at the same *m/z* 157. Since option gas (O_2) was introduced to eliminate the carbon, this condition increased the interference ions from $[BaOH]^+$ which simultaneously increased the background counts. As the concentration of acetonitrile increased under the gradient method, the carbon enhancement effect reduces the formation of metal oxides or hydroxides as shown by the equation 1, resulting in the lower baseline.

$$MO^+ + C \rightarrow M^+ + CO \qquad \text{(equation 1)}$$

3.2. Identification of PFCA compounds by HPLC-ICPMS/MS-ESI-MS

The identification of PFCA compounds was determined through the information recorded by ICPMS/MS and ESI-MS. HPLC-ESI-MS is the most common analytical method used to identify PFCA compounds [2,5,8,10,14,19–21]. In the negative ion mode of ESI, the H of carboxyl group deprotonated and the molecular ions are easily detected without derivatisation [1]. The same concept was applied in this study by coupling the HPLC not only to ESI-MS but also to ICPMS/MS. ICPMS/MS that acted as F-specific detector recorded any fluorine-containing compound separated by HPLC, while the ESI-MS gave the molecular information simultaneously. An overlay chromatogram of PFCA standards with ICPMS/MS

and ESI-MS detection shown in Fig. 3 indicating that the ICPMS/MS capable to detect fluorine compounds at *m/z* 157 by forming polyatomic ions of Ba with the F present in the compounds, while single ion monitoring in the ESI-MS confirmed the identity of each PFCA compound by their molecular masses.

In order to investigate the capability of the method for identifying any fluorine-containing compound, two sets of PFCAs standard (with and without neutralisation) were prepared and run under both isocratic and gradient methods. The methyl ester with a structure of $F\text{-}(CF_2)_n\text{-}COOCH_3$, where n= 6-10 could be produced from the reaction of PFCA and methanol when the stock solution is not fully neutralised. Storage and preparation of PFCA in methanolic solution also could lead to the formation of methyl ester through the reaction between alcohol or mixture of alcohol with mono- or poly-carboxylic acid [21–23].

It is apparent that the isocratically methanol method produced broad peaks in the ICPMS/MS which did not match the narrow Gaussian peaks in the ESI-MS (Fig. 3A). Interestingly, when using the acetonitrile method, the PFCAs were separated well and gave the expected peak shape in ESI-MS as well as in ICPMS/MS (Fig. 3B). However, additionally to the PFCA signals, a series of peaks suspected to be the methyl ester of each PFCA were also recorded in the ICPMS/MS as fluorinated compounds but no additional signals were recorded in ESI-MS. Under the isocratic methanol method, those extra compounds are not separated well and might co-elute with the PFCA peaks. An overlay ICPMS/MS chromatogram between neutralised and non-neutralised standards from both elution methods are shown in Fig. S1.

Longer storage of non-neutralised stock solution also increased the transformation of PFOA to the additional fluorinated compounds as illustrated by the single standard PFOA prepared after one-month storage of stock solution (Fig. 4A). This additional peak at 16 min is assumed to be the methyl ester of PFOA as it has the same retention time with methyl perfluorooctanoate (Me-PFOA) standard (Fig. 4A). However, no Me-PFOA peak was seen from the recorded chromatogram of ESI-MS (Fig. 4B). Methyl ester is well known to be produced under acidic conditions, hence the recommended neutralisation from the PFCA standard supplier. However, the esterification remained undetected when only ESI-MS (in negative as well as in positive mode) or APCI-MS (not presented here) were used. This would have implications on the quantification since any reaction would give a false calibration curve as has been discussed already elsewhere [21]. Although other stronger ionisation methods like electron impact could ionise these methyl esters, but this method is only applicable for GC separation and therefore not applicable for many applications in which all PFAS are analysed [1,21,24].

Hence, this example demonstrated well the usefulness of having a fluorine-specific detector for HPLC separation, which was capable of detecting any eluting fluorinated compound as long as its concentration was above the limit of detection for fluorine regardless if the compound was ionisable or not using soft ionisation methods such as ESI. Fig. S2 illustrates the overlay chromatograms of ICPMS/MS and ESI-MS for each single standard indicating that the ICPMS/MS was able to records the methyl ester peak while no peak was recorded from ESI-MS.

3.3. Quantification of PFCA compounds by HPLC-ICPMS/MS-ESI-MS

3.3.1. Calibration graph

Fig. 5 depicts the calibration graph of PFCA (C_6-C_{10}) standards under isocratic methanol elution method. The calibration graph for the isocratic methanol method displays similar sensitivity with any amount of F present in the compounds. This was expected and confirms previous studies showing that ICPMS/MS is generating compound unspecific (element-specific) detection for other elements and also here for fluorine [13,16,25]. When using the acetonitrile gradient method, the slope and therefore the fluorine response of the PFCAs and PFOS seem to differ slightly (Fig. 6). Repeated calibration graphs of the acetonitrile gradient method gave a similar pattern of the slopes (Fig. S3). This suggested that PFCAs with shorter carbon chain and a low number of fluorine (PFHxA) show smaller response than the long chained PFCAs, except for PFDA. Hence, there might be a molecular-specific effect. This may be the result of the plasma chemistry; the introduced amount of acetonitrile and its effect on the ionisation of fluorine to F^- and barium to Ba^{2+} and its ultimate formation of $[BaF]^+$ may not be fully compensated by the used retention time dependant response factor for fluorine. This however has not been seen by other elements such as arsenic or sulphur [16,26]. Another possibility is that the fluorine response was altered due to the difference in the transport efficiency into the plasma. However, the nebulisation efficiency may alter not only with the composition of the mobile phase (acetonitrile/water), but maybe also by the type of PFCA since these compounds are surface active and might therefore influence how much of these fluorinated compounds are eventually transported into the plasma during the nebulisation. The latter could be investigated by using an all consumption nebuliser when a nano-HPLC method would be used. This however was beyond the remit of this proof of concept study. In the next section, only gradient method will be discussed since all the fluorinated compounds are well separated using this method.

3.3.2. *Limit of detection (LOD)*

Calibrations of different PFCA and PFOS compounds were conducted and the limit of detections (LODs) were calculated from 3 times standard deviation (SD) of blank according to F concentration respectively. The LOD values listed in Table 2 shows a variation from 0.49 mg F L^{-1} to 0.84 mg F L^{-1} for gradient elution method of different PFAS respectively. These LODs could be lowered 5 times by increase the injection volume up to 100 µL instead of 20 µL. The reproducibility values between 2.2 to 29% of LODs was achieved showing the method capability to determine PFAS in the sub-ppm range (Table 2). The calculation for LOD and reproducibility is shown in SI.

3.4. Fluorine specific quantification

For real sample application, the method was further evaluated by spiking sub-ppb level of PFHxA and PFOA (around 0.5-2.4 µg F L^{-1} or 0.8-3.4 µg compound L^{-1}) into one deionised water (SMQ, 1000 mL) and two river waters (SRW1 and SRW2, 1220 mL each) with different concentration. The water samples were extracted using the same SPE procedure and measured under acetonitrile gradient method. The simultaneous fluorine specific detection with ICPMS/MS could help in to mine the ESI-MS data by identification where the fluorinated compounds elute so that the mass spectrum of this retention time can be scrutinised for fluorinated compounds. It is also can eliminate ESI-MS peaks which may candidates of fluorinated compounds according to their mass. The large front peak in river

water may contain fluorine-containing compounds which accumulate in the SPE. These eluting compounds are highly polar as indicated by the low retention time and could be fluoride although those polar compounds should not accumulate in SPE. Either the fluorinated compounds accumulating have been degraded during sample preparation to more polar compounds or the signal is an interference at the void volume which influence detection of background fluorine as $[BaF]^+$. No signal in ESI-MS indicated a fluorinated compound. However, this peak has no effect on the PFAS determination which elute later. As shown in Fig. 7A, no peak of a PFAS was seen from ICPMS/MS chromatogram of river water, although ESI-MS chromatogram shows multiple peaks of any non-fluorine containing compounds. In any case, ICPMS/MS method is a fluorine-specific detector as only fluorine-containing compounds were detected (Fig. 7B).

Based on individual calibration graph, the F concentration and the recovery of each spiked solution were calculated and shown in Table 3. The recoveries of the pure water were acceptable with 107-116%, while the recoveries for the river samples showed a slightly larger variability. The two PFCAs were recovered between 82-145%. This is acceptable since SPE has not been optimised with internal standards. In general, HPLC-ICPMS/MS was capable to measure river water samples containing fluorinated compounds at ppb and sub-ppb level using a SPE-based preconcentration method for the first time.

4. Conclusions

A novel method for non-targeted analysis of perfluorinated compounds has been described which enables the analyst to identify all fluorinated compounds regardless whether the compounds would ionise under ESI-MS conditions or not and whether a fluorinated standard is available. The analysis of spiked river water showed that this method could help to mine the huge ESI-MS data in identifying the unknown fluorinated compound. When combined with a preconcentration method such as SPE, the method is capable to quantify individual PFAS or other fluorinated compounds in the low to sub-ppb concentrations in river water. This makes ICPMS/MS as a potential method to screen water samples for organofluorines in which the mass balance of total organofluorines and identified organofluorines does not fit. This non-targeted organofluorines method is well suited to help the identification of a high proportion of so far undetected organofluorines.

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392 **Table 1:** HPLC-ICPMS/MS-ESI-MS parameter for fluorine compounds analysis

HPLC		Agilent 1290, UK	
	Column	ACE Excel 3 C18-Amide (100 mm x 3 mm x 5 um)	
	Column temperature	40^{O}C	
	Elution program	***Isocratic (A)***	***Gradient (B)***
		0-20 min: 70% B	0-0.5 min : 25% B 5 min : 50% B 10-27 min : 70% B
	Buffer	A: 0.1% formic acid	A: 2 mM ammonium acetate, 0.1% formic acid in water/acetonitrile (90:10 v/v)
		B: Methanol	B: 2 mM ammonium acetate, 0.1% formic acid in water/acetonitrile (10:90 v/v)
	Injection volume	100 µL	20 µL
	Flow rate	0.6 mL min^{-1}	0.5 mL min^{-1}
ICPMS/MS		Agilent 8800 Triple Quadrupole, UK	
	Mode	Organic mode	
	RF power	1600 W	
	Sampling position	7.8 mm	
	Nebuliser flow rate	0.77 L min^{-1} (Ar gas)	
	Makeup gas flow rate	0.33 L min^{-1} (Ar gas)	
	Option gas flow rate	0.07 L min^{-1} (*isocratic)* and 0.18 L min^{-1} (*gradient*) (mix O_2 and Ar gas)	
	Reaction gas flow rate	1.00 mL min^{-1} (O_2 gas)	
	Ba uptake flow rate	0.25 mL min^{-1} (*isocratic*) and 0.40 mL min^{-1} (*gradient*)	
	Monitored masses	$[BaF]^+$ *m/z* Q_1:157 -> Q_2:157	
ESI-MS		ESI-QTOF Compact (Bruker) and LTQ Orbitrap Discovery (Thermo Scientific)	
	Mode	Mainly negative (but also positive for the PFCA methyl esters)	
	Scan range	*m/z* 100-1000	

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Table 2: LOD of F for each PFCA compounds expressed as mg F L^{-1} and mmol F L^{-1} and the reproducibility of the LOD.

PFCA compound	LOD; mg F L^{-1} (mmol F L^{-1})	Reproducibility (%)
PFHxA	0.84 (0.044)	8.3
PFHpA	0.63 (0.033)	14
PFOA	0.49 (0.026)	17
PFNA	0.82 (0.043)	2.2
PFDA	0.55 (0.029)	6.4
PFOS	0.72 (0.038)	29

Table 3: F concentration and recovery on spiked PFCA compounds. (n=2).

Water	PFAS	PFHxA	PFOA
SMQ	F concentration ± SD (µg L^{-1})	1.3 ± 0.02	1.9 ± 0.06
	Recovery ± SD (%)	107 ± 2	116 ± 3
SRW1	F concentration ± SD (µg L^{-1})	0.73 ± 0.04	1.5 ± 0.07
	Recovery ± SD (%)	145 ± 9	92 ± 5
SRW2	F concentration ± SD (µg L^{-1})	1.6 ± 0.001	2.6 ± 0.01
	Recovery ± SD (%)	82 ± 0.03	109 ± 0.6

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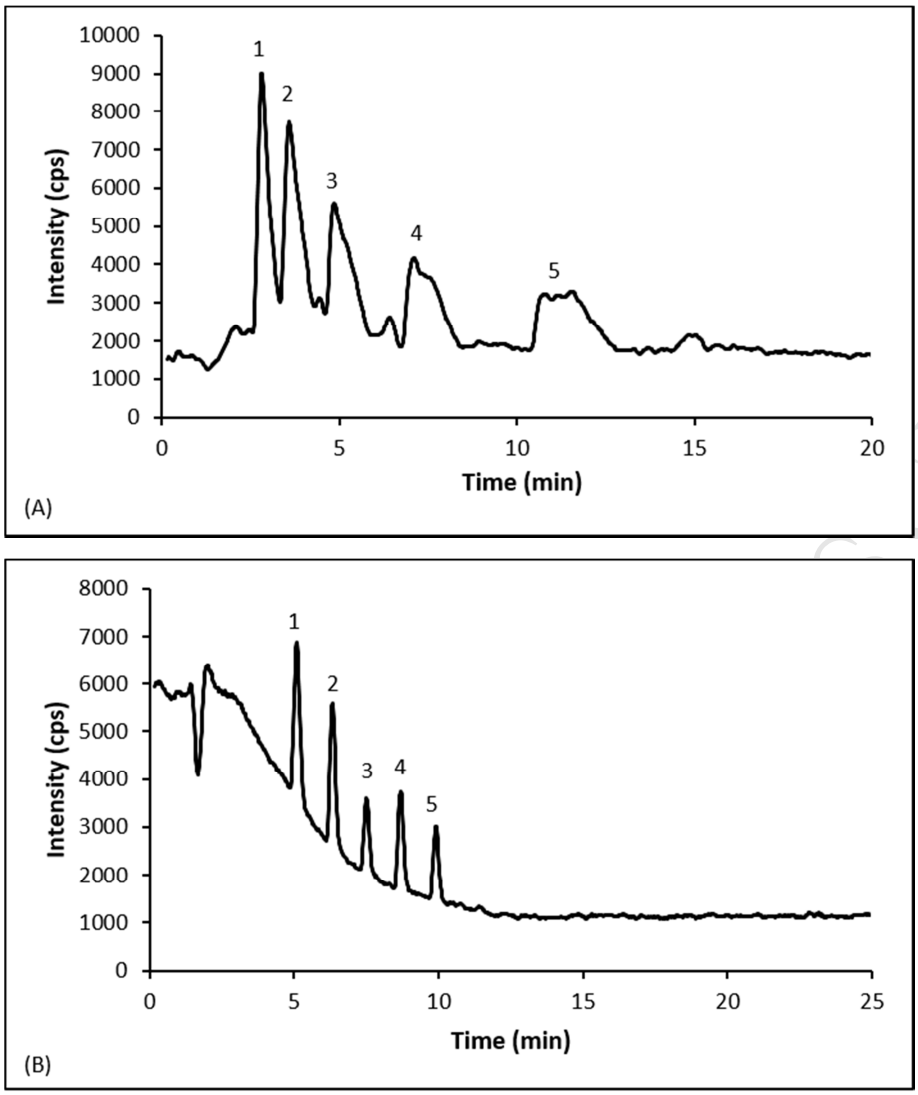

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408 **Fig. 1**: Chromatogram of PFCA compounds with approximate 5 mg F L^{-1} in each PFCA
409 compound under (A) isocratic elution of 70% methanol and (B) gradient of acetonitrile/water.
410 (1) PFHxA; (2) PFHpA; (3) PFOA; (4) PFNA; (5) PFDA.

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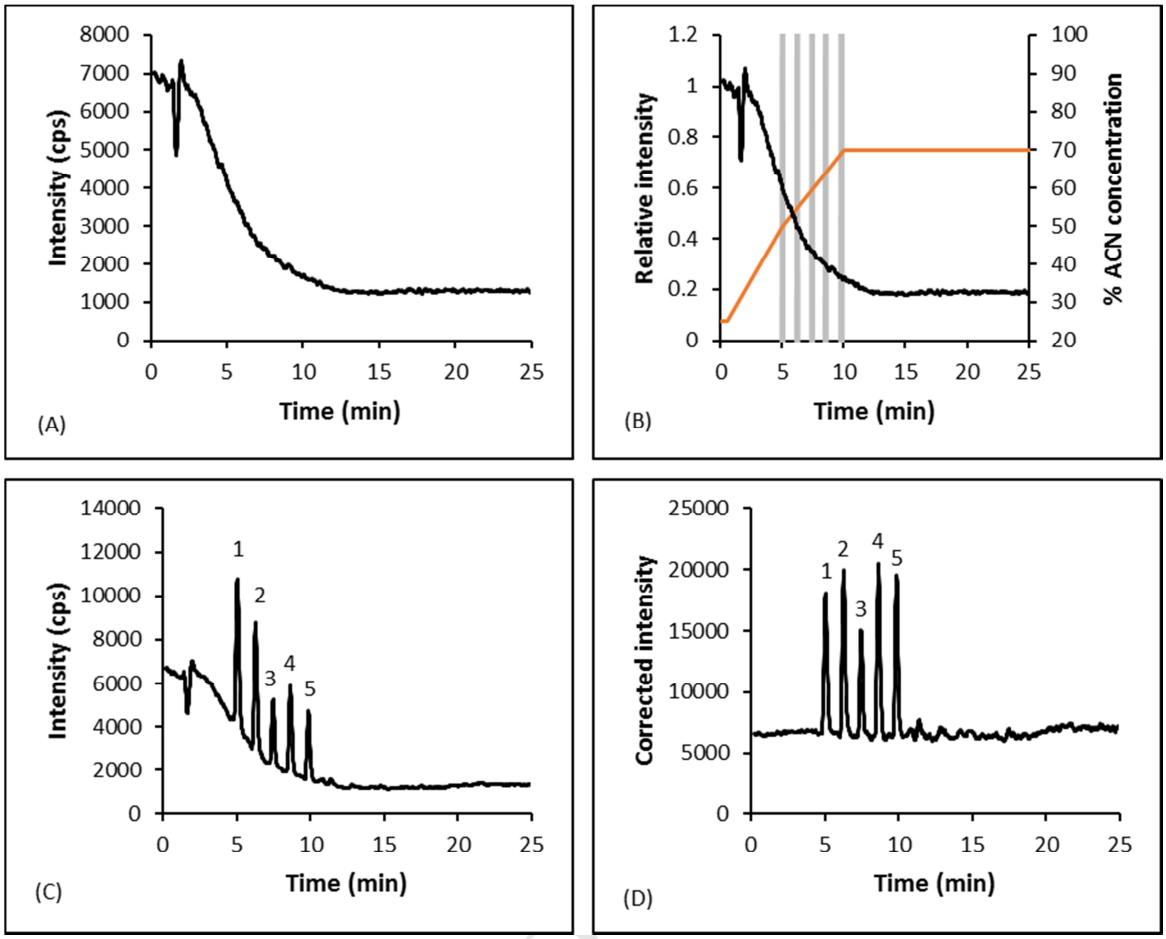
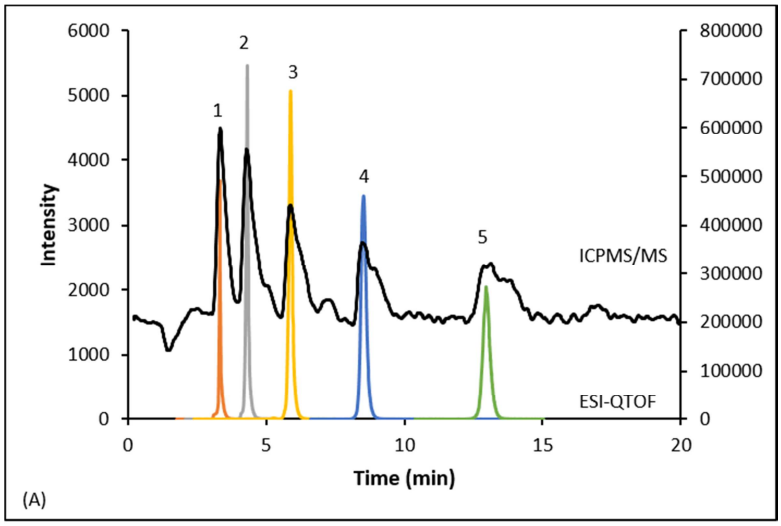


Fig. 2: Response factor applied to the recorded chromatogram. (A) Blank chromatogram run under gradient elution program. (B) Response curve with a retention time of each fluorine compound under different concentration of acetonitrile (orange line). (C) Recorded chromatogram of PFCA separation under gradient elution program. (D) Applied response factor on the corrected chromatogram of PFCA. The numbers labelled for each PFCA same as Fig. 1.



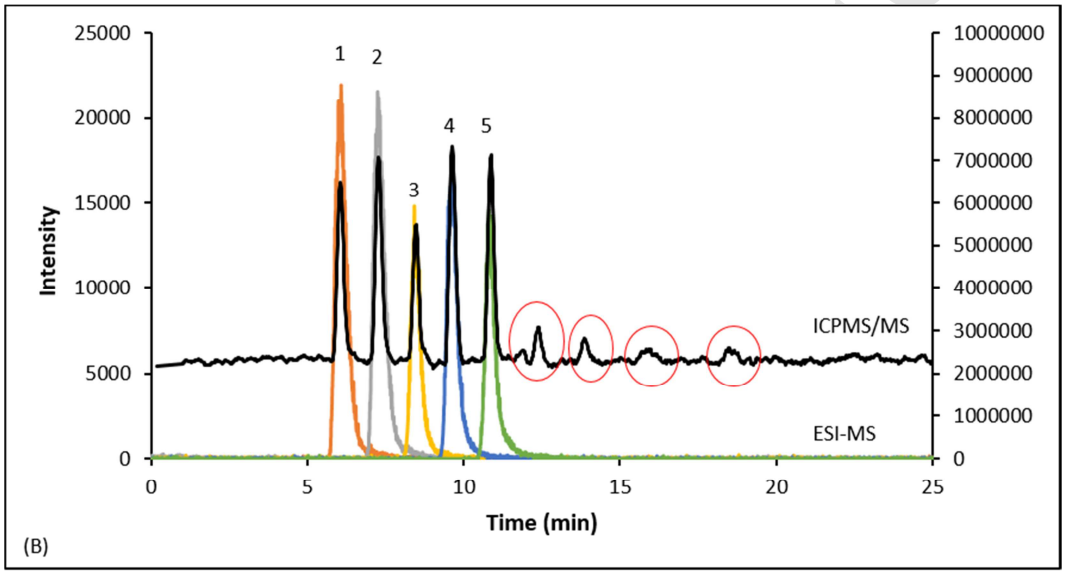


Fig. 3: An overlay chromatogram of PFCA compounds between ICPMS/MS and ESI-MS with (A) isocratic elution (approximate 5 mg F L^{-1} in each compound) and (B) gradient acetonitrile/water (approximate 10 mg F L^{-1} in each compound). The numbers labelled for each PFCA same as Fig. 1. The intensity of ICPMS/MS displayed on the left Y-axis while ESI-MS displayed on the right Y-axis. Additional peaks were illustrated in a circle.

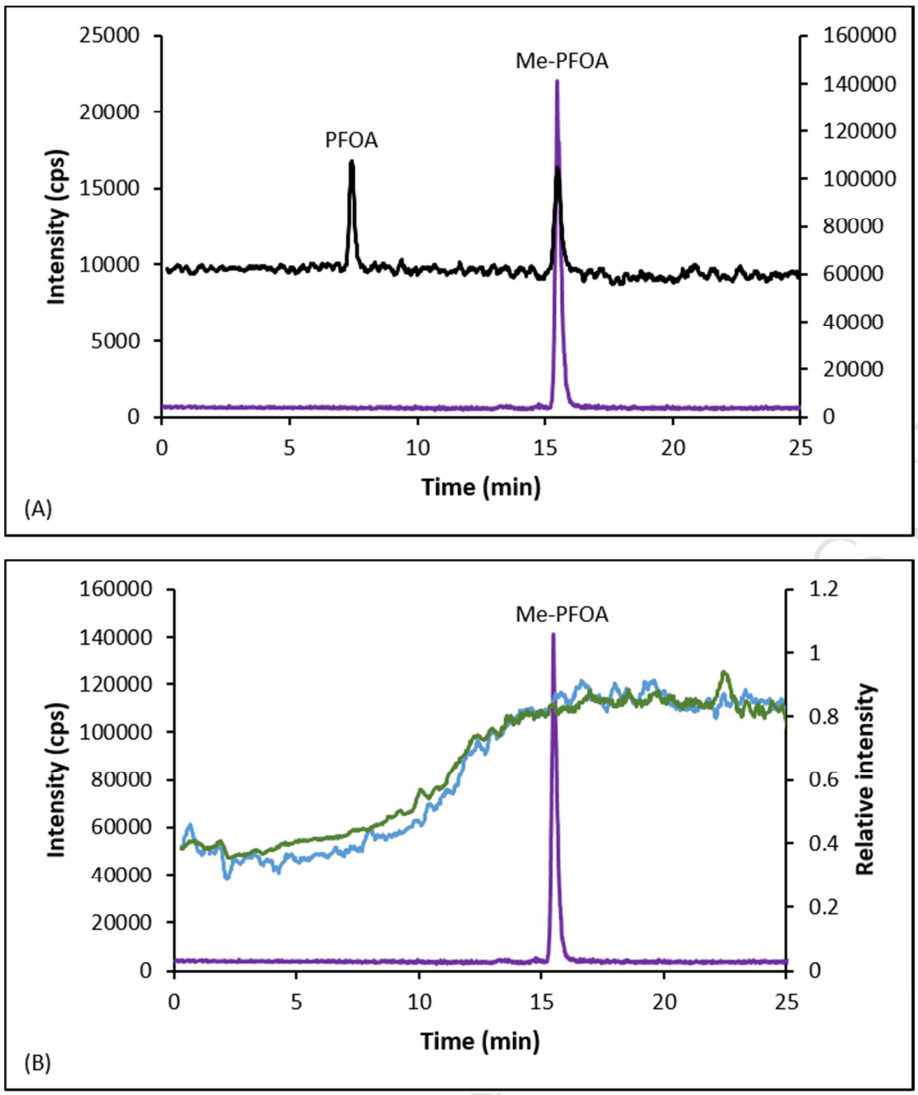


Fig. 4: An overlay chromatogram: (A) ICPMS/MS chromatogram of PFOA and Me-PFOA standards (approximately 10 mg F L^{-1}). PFOA standard after one-month storage illustrated in black colour, while Me-PFOA in purple colour. (B) ICPMS/MS and ESI-MS chromatogram (blue colour for positive mode while green for negative mode) of Me-PFOA standard. The intensity of ICPMS/MS displayed on the left Y-axis while relative intensity of ESI-MS displayed on the right Y-axis.

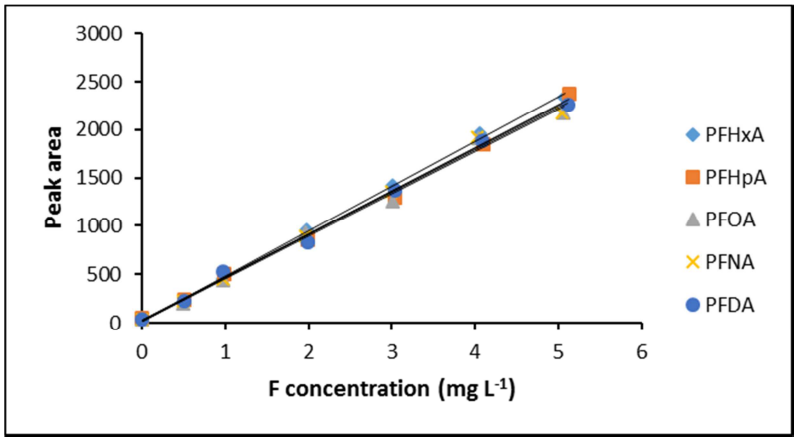


Fig. 5: Calibration graph of PFCA compounds with isocratic 70% methanol method.

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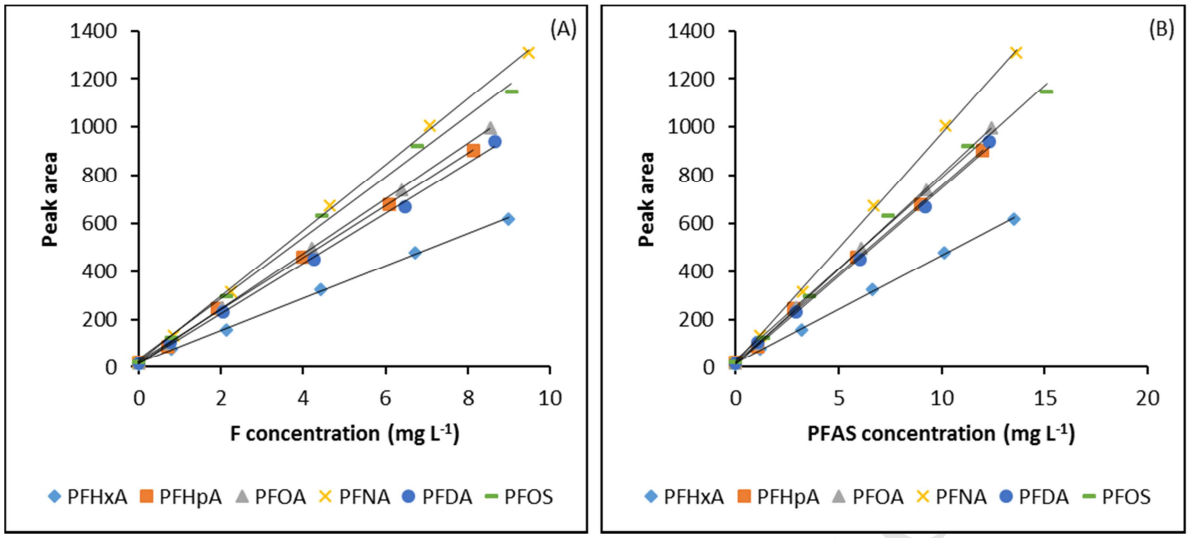

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452 **Fig. 6:** Calibration graph of each PFCA and PFOS compounds with gradient
453 acetonitrile/water based on: (A) F concentration (mg L^{-1}); (B) PFAS compounds
454 concentration (mg L^{-1}).

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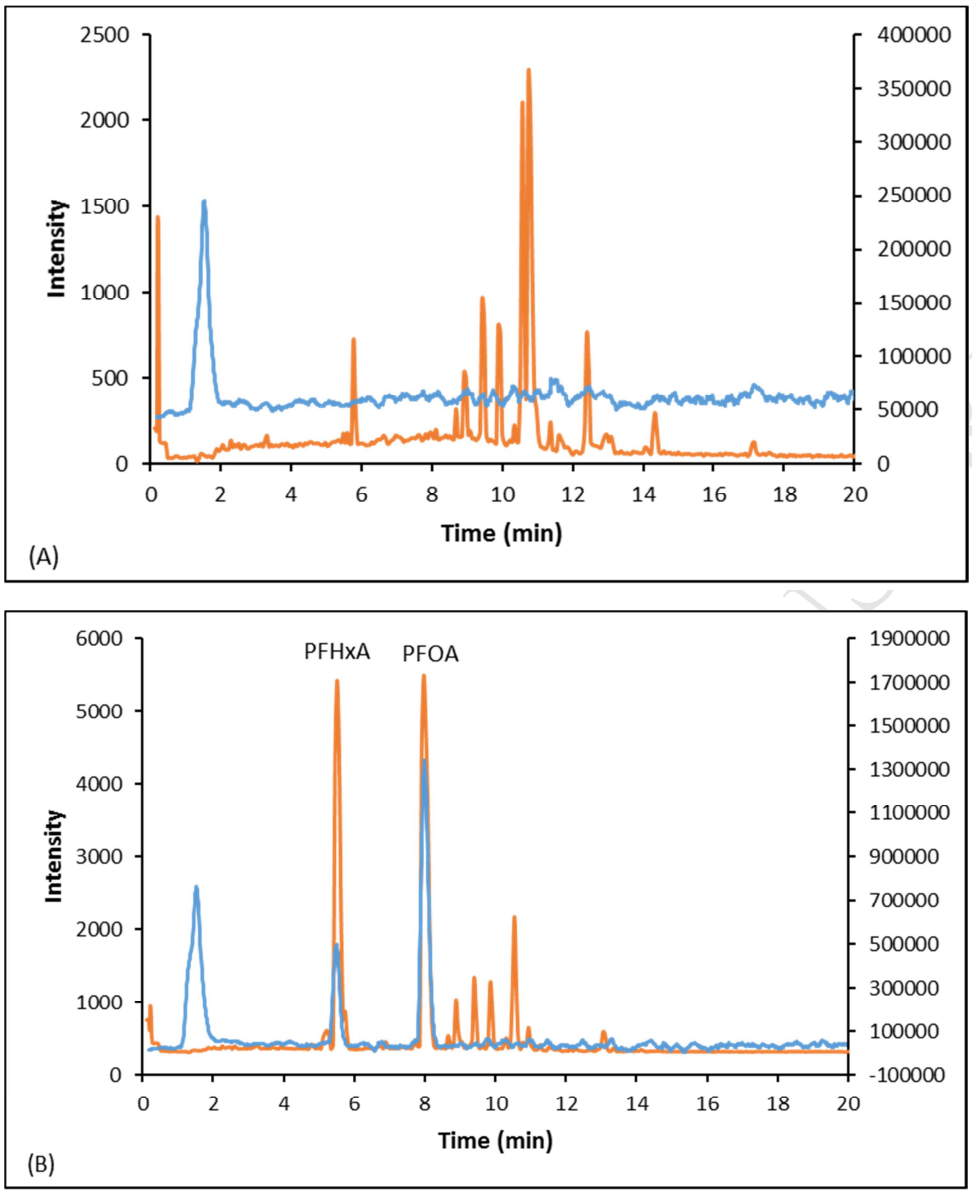

Fig. 7: An overlay ICPMS/MS (blue) and ESI-MS chromatogram (orange) of (A) river water and (B) spiked river water. The intensity of ICPMS/MS displayed on the left Y-axis, while the intensity of ESI-MS displayed on the right Y-axis.

Highlights:

- Post-column addition of a barium solution enables the detection of fluorines using ICPMS
- Reverse phase chromatography coupled to ICPMS and ESIMS enables the detection of perfluorinated compounds in spiked river water
- Perfluorinated carboxylic acids and their methylesters were detected using ICPMS
- Trace levels of perfluorinated carboxylic acids were determined at ppb or sub-ppb level in river water.