Journal of Hazardous Materials Letters 2 (2021) 100023

Contents lists available at ScienceDirect

Journal of Hazardous Materials Letters

journal homepage: www.elsevier.com/locate/hazl

Total and class-specific analysis of per- and polyfluoroalkyl substances in environmental samples using nuclear magnetic resonance spectroscopy

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ARTICLE INFO

Keywords:
Biosolids
Perfluorooctanoic acid
PFAS
Electrospray LC–MS
Nontarget analysis

ABSTRACT

This study reveals unique information that fluorine nuclear magnetic resonance (^{19}F-NMR) spectroscopy provides in the analysis of per- and polyfluoroalkyl substances (PFASs). Our results demonstrate that the intensity of the terminal -CF_3 signal can be used to determine the total PFASs regardless of headgroup. Characteristic chemical shifts of different classes of PFASs can also be observed, and are useful for differentiating between classes of PFAS. The NMR spectra of PFASs with ether linkages (e.g. GenX) show characteristic reference signals for both -CF_2 and -CF_3 signals that are useful for detection. Notably, ^{19}F-NMR can differentiate between PFASs, non-PFAS, and F^- ions, eliminating the need for sample clean-up even for complex samples. To illustrate this, the ^{19}F-NMR spectra of perfluorooctane sulfonic acid (PFOS) in biosolids extract and in clean solvent spiked with PFOS standard were compared, and showed a difference of < 0.3 % in their signal intensities. The lack of matrix effect is contrary to the suppression or enhancement observed in PFAS analysis by liquid chromatography with mass spectrometry, the most commonly used method for quantifying PFASs. This paper presents ^{19}F-NMR reference spectra for 34 PFASs and discusses the complementarity of this method with other approaches for the total and class-specific analysis of PFASs.

1. Introduction

Environmental contamination by per- and polyfluorinated alkyl substances (PFASs) has become of increasing concern as residues of these ubiquitous and persistent chemicals are tainting drinking water sources around the world (Lang et al., 2017; Domingo and Nadal, 2019; Akhbarizadeh et al., 2020). While PFASs have properties that are useful for a wide range of commercial and consumer product applications, high levels of PFAS residues enter the environment through leachate from landfills (Lang et al., 2017; Hepburn et al., 2019; Gallen et al., 2017; Wei et al., 2019), effluents from municipal and industrial wastewater treatment plants (Möller et al., 2010; Gallen et al., 2018; Zhang et al., 2013), land-application of biosolids (Venkatesan and Halden, 2021), and release from aqueous film forming foam (AFFF) at fire-fighting training facilities (Anderson et al., 2016; Barzen-Hanson et al., 2017). PFASs can bioaccumulate in humans (Buck et al., 2011; Li et al., 2018; Kelly et al., 2009), have been linked to certain cancers, and have a wide range of deleterious effects including hormone and immune system interferences, ulcerative colitis, and endocrine disruption (Jiang et al., 2015; Abbott et al., 2012; Pachkowski et al., 2019; C8 Science Panel, 2021), to name a few.

Due to multiple production techniques for PFASs (3M Company Technical Bulletin, 2021; Prevedouros et al., 2006; Sari Erkan, 2019), as well as the various transformations occurring in the environment (Sari Erkan, 2019), these compounds have a wide variation in their structural compositions. The United States Environmental Protection Agency (USEPA) CompTox database has identified over 9000 highly fluorinated substances with Chemical Abstracts Service numbers available in the global market, the majority being fluorinated polymers and fluorinated surfactants (USEPA, 2020). However, only over 750 PFASs have been identified to date using liquid chromatography with mass spectrometry (LC–MS) techniques (Zacs and Bartkevics, 2016; González-Barreiro et al., 2006; Point et al., 2019; Gremmel et al., 2017). There are many reasons for the limited identification of PFASs in environmental samples, such as poor ionization efficiency in LC–MS (Mullin et al., 2019), lack of reference materials, variable recoveries during extraction (González-Barreiro et al. (2006); Jahnke et al. (2007a); Rauert et al., 2018; Jahnke et al., 2007b; Ateia et al., 2019; Huang et al., 2018), and presence of unresolved isomers that do not have characteristic MS fragmentation patterns to facilitate identification. In addition, some PFASs such as hexafluoropropylene oxide dimer acid (Shoemaker and Tettenhorst, 2018) (HFPO-DA, also known as GenX) and neutral PFAS precursors and fluorotelomer alcohols (Peng et al., 2013) were shown to breakdown in source or have poor ionization efficiencies during LC–MS analysis (Berger and Haukås, 2005). With the advent of high-resolution mass spectrometry (HRMS) that is capable of accurate mass measurements and conducting fast scan rates to

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http://doi.org/10.1016/j.hazl.2021.100023
Received 9 February 2021; Received in revised form 10 April 2021; Accepted 12 April 2021
Available online 14 April 2021

achieve a low limit of detection (LOD) (Zacs and Bartkevics, 2016; Hu et al., 2005), more and more forms of PFASs are being discovered using non-target analysis (Choi et al., 2021). In addition, *in silico* approaches to estimate retention times (Guardian et al., 2021) and predict MS fragmentation (Yu et al., 2018), to diagnose potential structures, have proven useful in facilitating identification of unknown PFASs even without reference standards. However, high background noise from matrix-heavy samples results in numerous false positives and lengthy data analysis (Winkens et al. (2018); Liu et al. (2019)). While many types of sample preparation techniques can be used such as solvent (Mejia-Avendaño et al., 2017), ion-pair (Ahmadireskety et al., 2021), or solid phase extraction (SPE) (Guardian et al., 2020) to clean up samples, many PFASs may not be retained depending on the method. Inefficient sample extraction can lead to significant underestimation of PFAS content in environmental samples. Therefore, obtaining a balance between specificity and coverage in non-target screening is a critical limitation of HRMS in the discovery of unknown PFASs and in mass balance determination during sample treatment processes.

Total oxidizable precursor (TOP) assay, which is performed by degrading precursor PFASs into perfluorocarboxylic acid (PFCA) products followed by LC–MS analysis, has been used to quantify PFASs by class (Houtz and Sedlak, 2012). While TOP assay is effective in quantifying total oxidizable PFASs, this method comes with its own suite of limitations (Hutchinson et al., 2020). It requires one day of digestion with extensive cleanup, and the true quantity of PFASs may be underestimated as a result of incomplete digestion and/or losses during SPE. There is also no standard operating procedure for the TOP assay, leading to inconsistencies in the results obtained between laboratories. Another method that uses inductively coupled plasma mass spectrometry (ICP-MS) for fluorine-specific detection of PFASs after LC separation has been reported to quantify total PFASs in samples (Jamari et al., 2019). However, because current commercial ICP-MS instruments operate only in positive ionization mode, a post-column addition of Ba^{2+} solution is required to complex with the F^- ions that are generated from PFASs in the plasma, allowing for the detection of BaF^+ ions in the MS (Azua Jamari et al., 2018). While ICP-MS can be potentially used to quantify for total PFASs based on fluorine signal, this method suffers from high variability in signals due to interfering oxide or hydroxide ions, and changes in background counts as the organic modifier in the gradient mobile phase changes (Jamari et al., 2017). This ICP-MS method is derived from continuum source molecular absorption spectroscopy (CS-MAS), in which fluorinated compounds are pyrolyzed and then complexed with metals in a reaction chamber. The metal complex has its absorbance measured from 200 to 900 nm (Dittrich et al., 1984). Many diatomic metals can be used, but GaF is commonly measured at 211.248 nm for total PFASs analysis (Qin et al., 2012). Due to the specificity of the wavelengths corresponding to the diatomic molecule, background noise is low, and LODs have been reported down to μg/L levels (Qin et al., 2012). Even so, CS-MAS can only be used for total fluorine, with no structural data collected from the sample. Lastly, combustion ion chromatography (CIC) is used to combust any fluorinated compounds and convert them into hydrogen fluoride, which is measured by conductivity detection. Although preconcentration can be used with CIC, chloride ions can interfere with fluoride ion peaks. In addition, CIC only provides total fluoride concentration and does not give any structural information (Koch et al., 2020). Furthermore, if preconcentration is extensive, alkali metals can cause fouling of the combustion source, leading to inaccurate results.

There is a critical need to develop a method that allows detection of total PFASs and class-specific information of PFASs present in the sample in order to have more accurate assessment of the risks posed by these environmental contaminants. Total organic fluorine (TOF) analysis (Koch et al., 2020; Moody et al., 2001) based on ^{19}F nuclear magnetic resonance spectroscopy (^{19}F-NMR) that can capture all organofluorine compounds, including non-PFAS related chemicals, has been proposed as a suitable tool for total PFASs analysis. It is important to note that ^{19}F-NMR can differentiate PFASs from non-PFAS compounds and from F^- ions due to the distinguishable ^{19}F signal from the terminal trifluoromethyl moiety -CF_3 in the alkyl chain of PFASs. This -CF_3 signal is used to quantitate either a singular PFAS or total PFASs. The potential of ^{19}F-NMR for PFASs analysis in surface water samples has been demonstrated for perfluorooctane sulfonic acid (PFOS), perfluorohexane sulfonic acid (PFHxS), perfluorooctanoic acid (PFOA), and perfluorohexanoic acid (PFHxA) (Moody et al., 2001). However, ^{19}F-NMR has not been used in any other environmental samples, likely because of its inability to detect very low levels of PFASs. However, recent developments in fluorine-specific cryo probes could alleviate this issue, with detection limits possible at parts per trillion levels (Moody et al., 2001; Ellis et al., 2000). The main advantages of ^{19}F-NMR spectroscopy over LC–MS analysis are non-sensitivity to matrix effects, resulting in high reproducibility, inexpensive analysis, simplified or a complete lack of sample preparation, and the ability to quantify PFAS without the need for reference standards. Quantitation can be achieved based on the fluorine signal of any fluorinated internal standard, not necessarily a PFAS. For instance, hexafluorobenzene (HFB) can be mixed with the sample being analyzed and the intensity of the signal attributed to the 6 fluorine atoms in HFB can be used as a basis for calculating the amount of PFAS based on the intensity of the -CF_3 peak. Furthermore, ^{19}F-NMR can be used to characterize degradation of PFASs based on the information derived from the diagnostic ^{19}F shifts from each PFAS.

The goal of this study is to demonstrate the unique information offered by ^{19}F-NMR that can complement current methods for determining total PFASs in complex environmental matrices. We acquired the ^{19}F-NMR spectra for a series of PFASs with varying head groups, chain lengths, and branching in the alkyl chain. This is the first study that reports characteristic ^{19}F-NMR signals that are useful for identifying the classes of PFASs present in the sample, and for quantifying PFASs in highly complex matrices, such as biosolids. This study provides a proof-of-concept on the application of ^{19}F-NMR in both class-specific and total analysis of PFASs in real environmental samples.

2. Materials and methods

All PFAS standards were purchased as solid standards from Acros Organics, Alfa Aesar, Apollo Scientific, Fisher Scientific, Matrix Scientific, Santa Cruz Biotechnologies, Sigma Aldrich, Synquest, TCI, and Toronto Research Chemicals. A solution of 10 mM of each PFAS standard was prepared by dissolving accurately weighed amount of the solid in 700 μL deuterated methanol (Cambridge Isotope Laboratories, Andover, MA) in NMR tubes. ^{19}F spectra were collected on a Varian Inova 500 MHz NMR spectrometer, with a spectral width of -200 to -30 ppm. The acquisition time was 500 ms, the relaxation delay was 3 s, and observed pulse was 3.67 μs. All ^{19}F-NMR spectra were processed using MestreNova™ software (Santiago de Compostelo, Spain).

To compare the ^{19}F-NMR spectra of a matrix-heavy sample with a clean sample, 3.3 g of freeze-dried biosolids were combined with 10 mL of methanol inside a 15-mL Falcon tube. The falcon tube was sonicated for 30 min, followed by vortexing for 30 s. This cycle was repeated once more and then 3 mL of methanol were taken from the falcon tube and transferred into a clean 15-mL Falcon™ tube. The transferred sample was then centrifuged (10 min, 2169 g) and the supernatant was transferred to a third falcon tube. The supernatant was gently evaporated down to 200 μL under a N_2 stream; then, two 100 μL aliquots from this concentrated extract was transferred to two NMR tubes, labeled “matrix spiked” and “matrix blank”. The matrix blank was diluted up to 700 μL with deuterated MeOH and analyzed. The matrix spiked sample was spiked with HFB and PFOS to a final concentration of 50 μM each, and diluted up to 700 μL with deuterated methanol. A corresponding clean sample was made to contain 700 μL of deuterated methanol containing 50 μM of HFB and PFOS each. Data were accumulated for 1096 transients for the matrix

blank improve the sensitivity. The PFOS-fortified biosolid extract and reference standard were analyzed under the same analytical conditions except for the number of scans, which was adjusted to 400 for both extract and reference standard. The observed signal for PFOS was normalized to the internal standard HFB to assess the impacts of matrix on ^{19}F-NMR analyses.

3. Results and discussion

3.1. Comparison of ^{19}F-NMR Spectra for 8-carbon PFASs with different headgroups

The ^{19}F-NMR chemical shift of the terminal -CF_3 in PFASs can serve as a diagnostic tool for the presence of PFASs because it is not significantly affected by changes in the chemical environment of the distant headgroups. As shown for 8-carbon chain PFASs with six different head groups (Fig. 1), the chemical shifts for the fluorine atoms farthest from the headgroup remains relatively constant, around -82 ppm for terminal -CF_3, and around -127 ppm for the adjacent -CF_2 moiety. Fig. 1 shows that PFASs have similarities and differences that can be used to identify them as a class of compounds or as individual compounds. For instance, the terminal -CF_3 moiety in PFASs has an ^{19}F-NMR shift that is markedly separated from the -CF_2 signals (-110 to -130 ppm region) providing a signal that is characteristic of fluorinated alkyl chains, regardless of the head group in the opposite side of the molecule. In contrast, the fluorine atoms closest to the headgroup (labeled as "a" in Fig. 1) are the least shielded from the changes in the functional groups and therefore have chemical shifts that change the most. For instance, the $[CF_2]_a$ closest to the PFOS head group (-115.7 ppm) can be differentiated from the $[CF_2]_a$ closest to the PFOA head group (-120.2 ppm) or NMeFOSAA head group (-113.8 ppm). However, the fluorine shifts for $[CF_2]_a$ in 6:2 fluorotelomer alcohol (6:2 FTOH) (-114.7 ppm) and 6:2 fluorotelomer sulfonic acid (6:2 FTS) (-115.1 ppm) are very similar because they have the same connectivity to the adjacent -CH_2 and $[CF_2]_b$ moieties. This similarity in $[CF_2]_a$ shifts can be observed in PFASs that share the same head groups as shown in Fig. 2. Table 1 lists the chemical shift values for terminal -CF_3 and $[CF_2]_a$ for all tested PFASs showing the similarities and differences between classes, which can potentially be used for total and class-specific determination of PFASs.

3.2. Comparison of PFASs with the same head groups, but different carbon chain lengths

A series of carboxylated PFASs containing 7, 9, 10, and 14 carbons in the alkyl chain were analyzed in ^{19}F-NMR, as shown in Fig. 2. Within the PFCA class, the chemical shifts of the terminal -CF_3 and $[CF_2]_a$ are relatively constant at around -82 ppm and-120 ppm, respectively, with the exception of the PFPrA with the shortest carbon chain. This is due to the lack of fluorine in the short chain, leaving the $[CF_2]_a$ signal more shielded. On the other hand, the -CF_2 shifts in the internal carbon backbone chain (labeled a to m) provide unique "fingerprint" signals to distinguish between individual PFCAs. The unique chemical shifts observed in the inner -CF_2 moieties can provide information on the branching or ether groups, as shown for GenX in Fig. 3. While only the main classes of PFASs are listed in Table 1 with two characteristic terminal ends, all ^{19}F-NMR signals have been catalogued and are presented with their structures in Table S1.

3.3. Effect of branching and de-fluorination on ^{19}F-NMR shift

As seen in Table 1, the methoxy-perfluoro class has a significant ~30 ppm shift from all classes for both terminal ends, giving them a very characteristic chemical signal to differentiate from other PFAS contaminants in samples. This is especially important since these ether compounds are the new alternatives used in industrial processes (Scheringer et al., 2014; Gordon, 2011). The ether linkages that have been added in the molecule to increase degradability have large effects on the chemical shifts of the -CF_3 moieties they are adjacent to, as well as in the chemical shifts of all the fluorine signals analyzed. Notably, the methoxy compounds have a -CF_3 chemical shift around -56.8 ppm that can be used as a diagnostic signal when monitoring for these emerging PFASs. In addition to the -CF_3 shift, the -CF_2 nuclei in the ether linkage are deshielded due to the electronegativity of the oxygen (William and Dolbier, 2009), causing the chemical shift to have a more positive value. This is best exemplified in nonafluorodioxaheptanoic acid (NFDHA), in which there are two ether linkages (Fig. 3). The chemical shifts here are 40−50 ppm more positive than the closest analogue, perfluoro-4-methoxybutanoic acid (PFMBA) (see Table 1). GenX has a branching

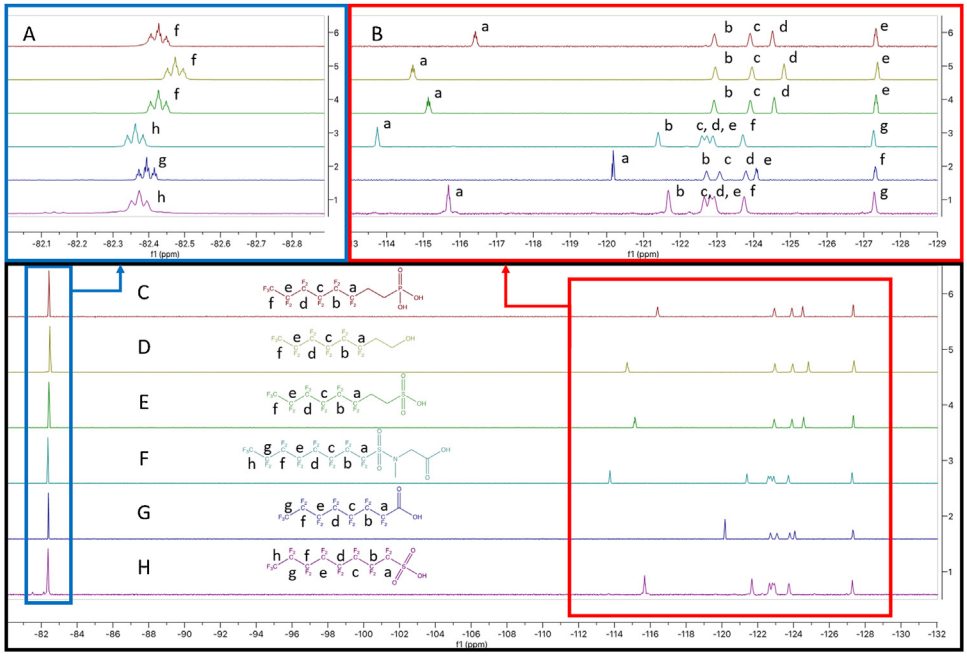

Fig. 1. Comparison of ^{19}F-NMR spectra of several 8-carbon chain PFASs: (A) shows zoomed in terminal -CF_3 signals at -82 ppm, and (B) shows zoomed in signals from the -CF_2 moieties of the test compounds; (C) 1H,1H, 2H, 2H-perfluorooctanesphosphonic acid, (D) 6:2 fluorotelomer alcohol, (E) 6:2 fluorotelomer sulfonic acid, (F) N-methyl perfluorooctane sulfonamidoacetic acid, (G) perfluorooctanoic acid, and (H) perfluorooctane sulfonic acid.

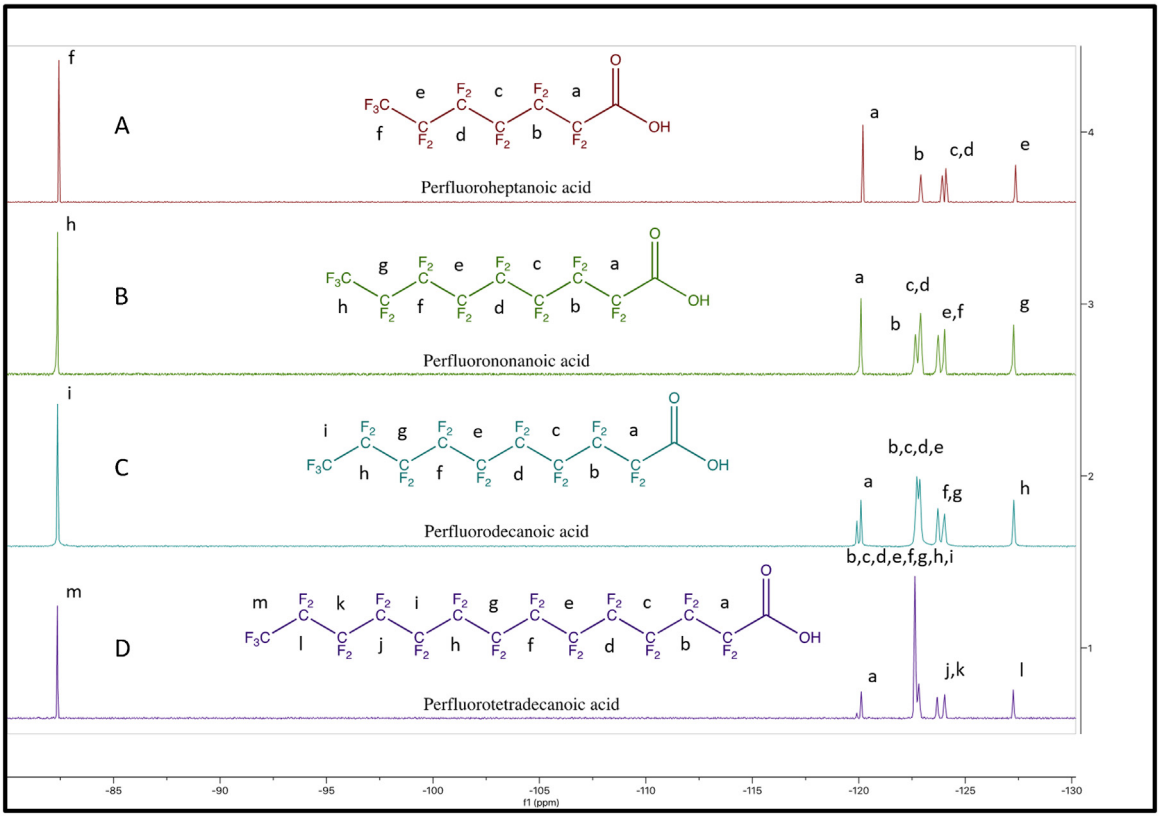

Fig. 2. Comparison within the PFCA class using (A) perfluoroheptanoic acid, (B) perfluorononanoic acid, (C) perfluorodecanoic acid, and (D) perfluorotetradecanoic acid to exemplify the shared -CF_3 peak but differing characteristic -CF_2 regions.

motif which also contributes to deshielding of neighboring nucleii (William and Dolbier, 2009). Due to the branching, ether linkage, and dual -CF_3 groups on GenX, it has a very unique NMR spectrum, providing the ability to distinguish these emerging PFASs in environmental samples. While having the more deshielded fluorine signals of the other ether linked PFASs, the -CF_3 signals never ascend into the -50 ppm range and two signals even go as far as -131 and -132 ppm, further negative than any other compound analyzed. Finally, the presence of two -CF_3 moieties in GenX cause a twin tower feature (Fig. 3C), making ^{19}F-NMR a very useful analytical tool for detecting GenX.

3.4. Use of ^{19}F-NMR in quantification of PFASs

Various studies have employed ^{19}F-NMR as a complementary analytical tool to the classic LC–MS or gas chromatography mass spectrometry (GC–MS) approaches for the quantification of total PFASs in environmental samples (Moody et al., 2001; Ellis et al., 2000, 2004; Ellis et al., 2001). Due to the low occurrence of fluorinated organic compounds in the environment and the fact that ^{19}F is the only naturally occurring isotope, ^{19}F-NMR can be used to characterize and quantify PFASs with minimal background signal interferences at the chemical shifts expected for PFASs. Unlike LC–MS methods, ^{19}F-NMR spectroscopy is not susceptible to matrix effects, and therefore has been used for in *vivo applications* and for quantitative analysis in complex matrices (Yu et al., 2013; Mattes et al., 2016). No extensive sample clean-up is needed, preventing the possible analyte loss during SPE. In addition, ^{19}F-NMR can provide quantitative measurements based on signal integration even without a reference standard, as explained earlier in the introduction. The larger the number of equivalent ^{19}F atoms, the stronger the signal becomes.

Table 1 provides a list of the common chemical shifts that can be used for the total quantification of PFASs regardless of the chain length of the carbon backbone or for class-specific analysis based on the type of headgroup or presence of branching in the carbon chain backbone (see Table 1). For instance, the terminal -CF_3 in methoxy-PFASs has a chemical shift around -57 ppm, which can be used to quantify for PFASs in this class. In addition, the ^{19}F-NMR shift characteristic of the -CF_2 group closest to the carboxylic head group is around -120 ppm, and the -CF_2 group closest to the sulfonic acid head group has a chemical shift of about -115 ppm, which can differentiate between these two major classes of PFASs in the environment, and can be used to identify members of these classes with four or more carbons in the alkyl chain. Similarly, the terminal -CF_3 shift shared by most PFASs (except by those with ether moieties) can serve as a diagnostic signal for quantifying PFASs, including those that are neutral and poorly ionizable in LC–MS. The use of these characteristic ^{19}F-NMR shifts for quantification will allow mass balance calculations in environmental fate and treatment studies.

To illustrate the applicability of ^{19}F-NMR in quantitative analysis of PFASs in a complex matrix, a comparison of a PFOS-fortified biosolids extract (50 μM) with PFOS reference standard (clean matrix) was performed (supplementary information, Fig. S1). The same chemical shift for the signature -CF_3 moiety was observed between the biosolids sample and reference standard (-82.4 ppm). This suggests that the complex biosolids matrix does not impact the resonance frequency of the fluorine atoms along the alkyl chain. More notably, the normalized areas of the PFOS -CF_3 signal in both samples were within 0.285 % of each other, which indicates that ^{19}F-NMR signals are mostly unaffected by any co-extracted matrix components (Fig. S1). Further evaluation of matrix impacts on ^{19}F-NMR signal intensities needs to be evaluated to determine the method detection limits in various matrices and sensitivity over a wider concentration range. Unlike with ^{19}F-NMR, other analytical methods used for trace chemical analysis, such as LC–MS, are significantly impacted by the effects of matrix (Smeraglia et al., 2002; Kebarle and Tang, 1993; Yen et al., 1996). With non-NMR analytical methods, extraction and clean-up procedures are imperative and can lead to analyte losses within samples. Sample preparation for sewage sludge and

Table 1
Chemical shifts of PFAS terminal -CF_2 and -CF_3 moeities. Chain length refers to the number of carbons in the backbone chain of the molecule. *HFPO-DA's structure has a -CF signal closest to the acid end, which is the chemical shift reported, instead of a -CF_2.

Class	Chain length	Standards	Abbreviation	$[-CF_2]_a$ closest to acid end (ppm)	Terminal -CF_3 (ppm)
Carboxylic	3	Pentafluoropropionic acid	PFPrA	−123.4	−84.9
	5	Perfluoropentanoic acid	PFPeA	−120.5	−82.6
	6	Perfluorohexanoic acid	PFHxA	−120.2	−82.5
	7	Perfluoroheptanoic acid	PFHpA	−120.2	−82.4
	8	Perfluorooctanoic acid	PFOA	−120.2	−82.4
	9	Perfluorononanoic acid	PFNA	−120.1	−82.4
	10	Perfluorodecanoic acid	PFDA	−120.1	−82.4
	11	Perfluoroundecanoic acid	PFUnA	−120.2	−82.4
	13	Perfluorotridecanoic acid	PFTrDA	−120.2	−82.4
	14	Perfluorotetradecanoic acid	PFTeDA	−120.1	−82.4
Sulfonic	1	Trifluoromethanesulfonic acid	TFMS	–	−80.2
	4	Perfluorobutanesulfonic acid	PFBS	−116.0	−82.3
	5	Perfluoro-1-pentanesulfonic acid	PFPeS	−115.7	−82.5
	6	Perfluorohexanesulfonic acid	PFHxS	−115.7	−82.4
	7	Perfluoro-1-heptanesulfonic acid	PFHpS	−115.7	−82.4
	8	Potassium perfluorooctanesulfonate	PFOSK	−115.7	−82.4
	10	Perfluoro-1-decanesulfonic acid	PFDS	−115.7	−82.4
Fluorotelomer Sulfonic acid (FTSA)	6	1H, 1H, 2H, 2H-Perfluorohexane sulfonic acid	4:2FTS	−115.4	−82.7
	8	1H, 1H, 2H, 2H-perfluorooctane sulfonic acid	6:2FTS	−115.1	−82.4
	10	1H, 1H, 2H, 2H-Perfluorodecane sulfonic acid	8:2FTS	−115.1	−82.4
Methoxy-perfluoro carboxylic	4	Perfluoro-3-methoxypropanoic acid	PFMPA	−89.3	−56.9
	5	Perfluoro-4-methoxybutanoic acid	PFMBA	−86.9	−56.8
	4	Perfluoro(2-ethoxyethane)sulfonic acid	PFEESA	−83.7	−88.3
	5	Nonafluoro-3,6-dioxaheptanoic acid	NFDHA	−78.9	−57.0
	5	Hexafluoropropylene oxide dimer acid (GenX)	HFPO-DA	−132.9*	−82.9
Fluorotelomer alcohols (FTOH)	6	1H, 1H, 2H, 2H-Perfluorohexanol	4:2FTOH	−115.0	−82.7
	8	1H, 1H, 2H, 2H-Perfluorooctanol	6:2FTOH	−114.7	−82.5
	10	1H, 1H, 2H, 2H-Perfluorodecanol	8:2FTOH	−114.7	−82.4
	12	1H, 1H, 2H, 2H-Perfluorododecanol	10:2FTOH	−114.7	−82.4
Phosphonic acids	8	1H, 1H, 2H, 2H-Perfluorooctanephosphonic acid	PFOPA	−116.4	−82.4
	12	1H, 1H, 2H, 2H-Perfluorododecylphosphonic acid	PFDOPA	−116.4	−82.4
Aminated	8	N-methyl perfluorooctane sulfonamidoacetic acid	NMeFOSAA	−113.8	−82.4
	8	N-ethyl perfluorooctane sulfonamidoacetic acid	NEtFOSAA	−114.0	−82.4
	8	Perfluoro-1-octanesulfonamide	FOSA	−115.1	−82.4

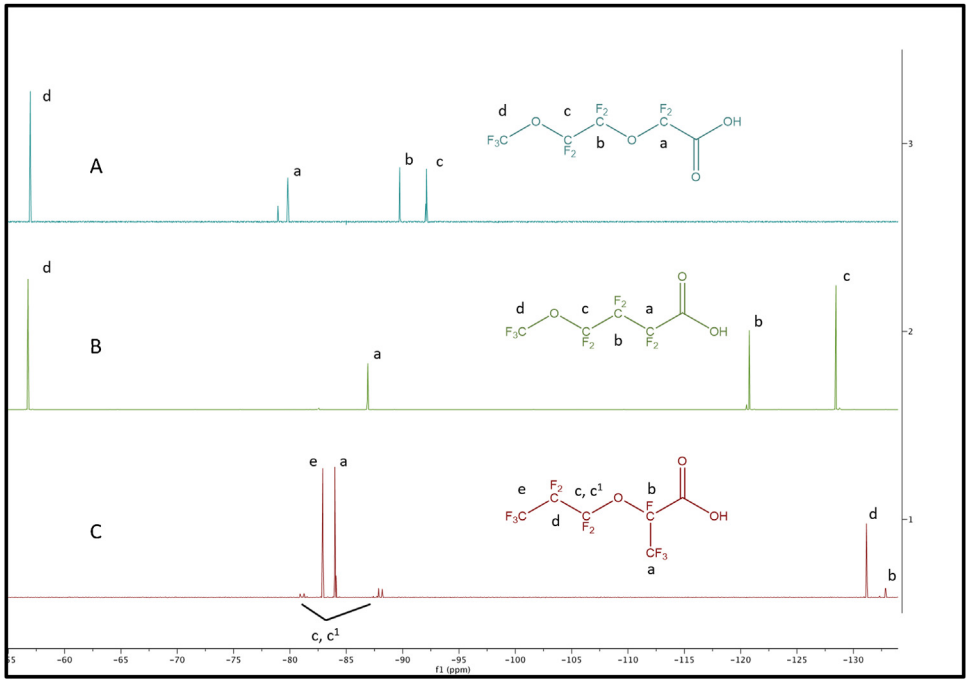

Fig. 3. Comparison of (A) nonafluorodioxaheptanoic acid (NDFHA), (B) perfluoromethoxybutanoic acid (PFMBA), and (C) GenX (HFPO-DA).

biosolids (Higgins et al., 2005; Zhang et al., 2018; USEPA, 2007) often require a pre-dilution factor to minimize the impacts of matrix on the accuracy of quantification.

One of the primary challenges of using ^{19}F-NMR for quantification is the high detection limit that is inherent with this technique. The intensity of NMR signals depends on the number of scans used in sample analysis. Increasing the number of scans improves the LOD, albeit at the cost of analysis time. However, the lack of matrix interferences in ^{19}F-NMR provides an opportunity to preconcentrate large amounts of sample without having to worry about the co-extracted matrix affecting the ^{19}F-NMR signal. Lower method LODs can be achieved with large pre-concentration factors, allowing for the detection of PFASs at environmentally relevant concentrations. For example, in the analysis of groundwater samples, a detection limit of 50 nM (25 μg/L for PFOS) in vial can be potentially achieved by concentrating 1-L samples, where concentrations between 4−4300 μg/L have been reported (Anderson et al., 2016). In fact, ^{19}F-NMR has been used to achieve ng/L detection limits in surface water samples for the analysis of the total PFASs (Ellis et al., 2000) through integration of the signature -CF_3 moiety.

4. Conclusions

In this work, we have shown the advantages of ^{19}F-NMR as a tool for total and class-specific analysis of PFASs. Characteristic chemical shifts for each tested PFAS were determined to be useful for identification and quantification of emerging PFASs. It is important to note that the sample matrix has minimal impact on the signal intensity or chemical shifts of ^{19}F, providing an important opportunity for quantifying PFASs in highly complex samples without the extensive clean up that typically results in sample losses. Furthermore, ^{19}F-NMR has been shown by others to be useful at environmental levels and for total organic fluorine measurements. Future research should evaluate chemical shifts of available degradation products of the new ether-containing PFASs to provide reference spectra and to confirm if the characteristic terminal -CF_3 shifts are maintained between the degradation products and the ether linked PFASs. Finally, optimization of instrument parameters such as relaxation delay and number of transients should be performed to improve quantitative assessment of total PFASs in complex environmental samples.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgements

The authors acknowledge National Science Foundation (NSF), Award# 1905274 to DSA. We would like to acknowledge Dr. Dinesh Sukumaran for reviewing the manuscript, and the graduate assistants, Zackary Gregg and Thomas Sobiech, from the University at Buffalo NMR center for their assistance in the instrumentation used. Any opinions, finding, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the NSF.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.hazl.2021.100023.

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