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Quantitative detection of trace perfluorinated compounds in environmental water samples by Matrix-assisted Laser Desorption/Ionization-Time of Flight Mass Spectrometry with 1,8-bis(tetramethylguanidino)-naphthalene as matrix

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ABSTRACT

Determination of perfluorinated compounds (PFCs) is very important because of their potential hazards to the environment and human health. In present work, 1,8-bis (tetramethylguanidino)-naphthalene (TMGN), a superbasic proton sponge, was firstly employed as the matrix for quantitative detection of acidic PFCs in environmental water samples by Matrix-assisted Laser Desorption/Ionization-Time of Flight Mass Spectrometry (MALDI-TOF-MS). Several acidic PFCs, such as perfluorooctanesulfonate (PFOS) and perfluorooctanoic acid (PFOA), were selected as model analytes for demonstrating the feasibility of the detection method. The results showed that deprotonated ions of these PFCs were detected without any other matrix ions interference. The achieved sensitivity with TMGN for PFOS detection was ten-fold higher than that with 1,8-bis (dimethyl-amino)-naphthalene (DMAN) which was used for the detection of fatty acid by MALDI-TOF-MS. The high sensitivity of this method made it feasible to monitor and quantify acidic PFCs in complicated environmental water samples. Furthermore, a novel combined strategy of solid phase extraction (SPE) followed by MALDI-TOF-MS detection was developed for quantifying PFCs in environmental water samples. The calibration curves with a wide linear dynamic range (0.1–10 ng L^{-1} for PFOS, PFHxS, and PFBS, and 0.5–50 ng L^{-1} for PFOA, PFNA, and PFDA.) were obtained. The limit of detection (LOD) for PFOS of this method was 0.015 ng L^{-1} (a signal-to-noise ratio of 3), which was lower than the LOD (0.036 ng L^{-1}) obtained by high-pressure liquid chromatography/tandem mass spectrometry (LC–MS/MS) method. Moreover, the strategy was used to detect the selected PFCs in water samples collected from Xiaoqinghe river and Gaobeidian wastewater. The achieved concentrations of PFCs were closed to those obtained by LC–MS/MS method. It is indicated that the proposed MALDI-TOF-MS method with TMGN as the matrix is much reliable and can be used as an alternative method to detect trace PFCs in environmental water samples.

1. Introduction

Perfluorinated compounds (PFCs) are a class of organic chemicals, which have been widely used in consumer products and industrial processes [1]. The family of PFCs includes perfluoroalkyl sulfonates (such as PFOS, perfluorobutyl sulfonate (PFBS), and perfluorohexyl sulfonate (PFHxS)), perfluoroalkyl carboxylic acids (such as PFOA and other short-chain or long-chain perfluoroalkyl acids), and sulfonamide derivatives (perfluorooctane sulfonamide (PFOSA)). Distributing widely in the environment, most of PFCs can exist for a long time and have bioaccumulation properties and toxic effects [2–5]. Recently, many studies had shown that PFCs induced reactive oxygen species production that affect actin filament remodeling and increase endothelial permeability of human microvascular endothelial cells [5], and they also had potential toxicity to induce liver cancer [6–8]. Because of the potential hazards of PFCs to the environment and human health, PFCs have been regarded as a new class of environmental contaminants and been banned from use. However, PFCs still present in the environment. Therefore, it is necessary to develop fast and sensitive analytical techniques for PFCs detection.

In recent years, many analytical methods have been developed to detect PFCs in environmental and biological matrices. For example, Ehresman et al. compared the levels of PFBS, PFHS, PFOS, and PFOA in the whole blood, plasma and serum samples collected from

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the same individuals by using high-pressure liquid chromatography/tandem mass spectrometry (LC–MS/MS) [9]. Maestri [10] treated tissue samples with trifunctional (t-C_{18}) and strong anion-exchange (SAX) SPE, and then measured the concentration of PFOS and PFOA in the samples by a system coupled with LC and a single quadrupole MS. The LOD of this method was 0.1–0.2 ng/g. Powley [11] developed a LC–MS/MS method to determine the distribution of PFCs in Zooplankton, Arctic cod, and seal tissues from the western Canadian Arctic. LC–MS/MS has high precision, high sensitivity, and wide linear range for PFCs in complicated matrices, but low instrument blank is extremely needed [12]. Stainless steel line fittings and tubing are needed in order to avoid the fluorinated compound contamination, which increases experimental cost greatly. On the other hand, in LC–MS/MS analysis, the prepared samples must be free of salt or matrices in order to avoid chromatographic system blocking and to keep the status of ionization source spraying fluently. Therefore, alternative methods, which are easy to operate, with high salt-resistance and high sensitivity, but without fluorinated compound contamination, are needed.

MALDI-TOF-MS as a "soft" ionization mass spectrometry, has been widely used in fields of proteomics [13,14], genomics [15], biological imaging [16], sugar, and polymer analysis [17,18]. The target analytes are macromolecules (the molecular weight, M.W. > 1000 Da, such as proteins, nuclear acids and polymers). To detect small molecules (M.W. < 1000 Da) by MALDI-TOF-MS, conventional matrices, such as α-cyano-4-hydroxyl-cinnamic acid (CHCA) and 2,5-dihydroxyhenzoic acid (DHB), generate matrix ions in the low molecular mass range (m/z for 0–1000 Th) to interfere the detection of small target molecules. Many special matrices, such as porphyrin [19], 9-aminoacridine [20], nanomaterials [21–25], and 1,8-bis (dimethyl-amino)-naphthalene (DMAN) [26], were developed for small molecule analysis. These matrices partly avoided matrix ion interference in the low molecular mass range, and obtained high sensitivity. However, there are also some shortages. For example, porphyrin was only suitable for saturated fatty acids analysis, and 14 Da shift occurred when it was used for unsaturated fatty acids; nanomaterials falled off from MALDI target during the desorption and led to instrumental contamination. Therefore, it is necessary to develop novel matrices for small molecule detection by MALDI-TOF-MS.

For PFCs analysis, surface-assisted laser desorption/ionization mass spectrometry (SALDI-MS) was used for PFOS and PFOA detection [27,28]. However, SALDI-MS is only suitable for perfluoroalkylcarboxylic acids with chain lengths below C6. To the best of our knowledge, quantification of PFCs by MALDI-TOF-MS with organic compound as the matrix has seldom reported. Compared with LC–ESI-MS/MS for PFCs analysis, MALDI-TOF-MS has higher salt tolerance, but does not have perfluorinated compound contamination.

In present study, 1,8-bis (tetramethylguanidino)-naphthalene (TMGN), a superbasic proton sponge, was employed as the matrix for quantitative detection of acidic PFCs by MALDI-TOF-MS for the first time. Furthermore, a novel strategy combining SPE enrichment and MALDI-TOF-MS with TMGN as the matrix was developed and applied for PFCs quantification in environmental water samples.

2. Experimental

2.1. Materials

Perfluorooctanoic acid (PFOA, 95%), perfluorononanoic acid (PFNA, 97%), and perfluorodecanoic acid (PFDA, 97%) were bought from Alfa Aesar (Lancashire, England), potassium salts of perfluorobutane sulfonate (PFBS, ≥98%), perfluorohexane sulfonate (PFHxS, ≥98%), perfluorooctane sulfonate (PFOS, ≥98%), 1,8-bis(tetramethylguanidino)-naphthalene (TMGN, ≥95%), and 1,8-bis(dimethyl-amino)-naphthalene (DMAN, ≥98%) were obtained from Sigma–Aldrich (Steinheim, Germany). The internal standards $^{13}C_4$-PFOS (≥98%) and $^{13}C_4$-PFOA (≥98%) were obtained from Wellington Laboratories (Guelph, Ontario, Canada). Methanol (HPLC grade) was bought from Fisher Scientific (Fair Lawn, New Jersey). HPLC grade acetonitrile (CH_3CN) was obtained from J.T. Baker (Phillipsburg, NJ, USA). Trifluoroacetic acid (TFA) was purchased from Aldrich (Steinheim, Germany). α-Cyano-4-hydroxycinnamic acid (CHCA) was provided by Bruker Doltonics Cop. The C_{18}-SPE cartridge (500 mg, 6 mL) was purchased from Alltech Company (Deerfield, IL, USA). PEG 600 sulfate was purchased from Sigma–Aldrich (Steinheim, Germany). Ultra-pure water was prepared by Milli-Q system (Millipore, Milford, MA, USA).

2.2. Sample preparation

All stock solutions of PFCs were prepared in methanol and stored in polypropylene (PP) tubes or vials (rinsed with methanol and water before use) at 5 nmol/μL, and then diluted with methanol to the desired concentration. TMGN was prepared at the same concentration as the analytes in methanol. 5 μL of each analyte was premixed with equal molar of TMGN in polypropylene tubes; the mixture was vortexed for 30 s. Then, 1 μL of the final mixture was directly spotted on a 384-well MALDI target plate (AnchorChip TM target plate, provided by Bruker Doltonics, Germany), followed by drying at room temperature for MALDI-TOF-MS analysis.

2.3. Environmental water sample collection and preparation for MALDI-TOF-MS analysis

Water samples were collected from different districts of Beijing, China. Tap water samples were obtained from the water tap in our lab in Haidian district, Beijing. River water samples were collected from Xiaoqinghe river (Haidian district, Beijing). Wastewater samples were collected from Gaobeidian wastewater treatment plant (Chaoyang district, Beijing). All the samples were filtered with a glass fiber filter to remove suspended solids. The filtered samples were stored in polypropylene bottles at 4 °C until analysis.

Solid phase extraction (SPE) with C_{18}-SPE cartridge (500 mg, 6 mL) was used as sample pretreatment method to enrich PFCs in water samples. 1 μL of $^{13}C_4$-PFOS (1.0 μg/mL) and 1 μL of $^{13}C_4$-PFOA (5.0 μg/mL) were added to the water samples as internal standards prior to extraction. The extraction and cleanup steps were as follow: firstly, C_{18}-SPE cartridges were pretreated with 10 mL of methanol and 10 mL of Milli-Q water; secondly, 500 mL of each water sample was loaded onto the pre-conditioned C_{18}-SPE cartridge at a flow rate of 1 mL/min, then the cartridges were dried under vacuum for 3 h; thirdly, 4 mL of methanol were used to elute PFCs from the cartridge and the eluent was collected in glass tubes which had been washed with 1:1 (v/v) methanol/acetone. The resulting eluent was concentrated to less than 0.1 mL under nitrogen flow and diluted to 0.1 mL in methanol for MALDI-TOF-MS analysis.

2.4. The procedural blanks and method validation

To eliminate any artificial contamination from sampling to analysis, all the containers used in the experiment were cleaned with methanol at least three times prior to use, and dried at 80 °C for 6 h. The blanks were performed with ultra-pure water (no PFCs contained) and handled with the same extraction and analysis procedures as the real water samples. None of the blanks showed significant contamination.

The calibration curve was performed with the detection of PFCs (PFOS, PFHxS, PFBS, PFOA, PFNA, and PFDA) by using 500 mL of

ultra-pure water (no PFCs contained) spiked with standard PFCs in the range of 0.1–10 ng L^{-1} for PFOS, PFHxS, and PFBS, and 0.5–50 ng L^{-1} for PFOA, PFNA, and PFDA. 1 ng of $^{13}C_4$-PFOS and 5 ng of $^{13}C_4$-PFOA were added to the water samples as internal standards prior to SPE. Limit of detections (LODs) which were defined as the concentrations that yielded an S/N ratio of higher than or equal to 3, were determined by SPE of the spiked distilled water samples. Precision and accuracy were evaluated at two concentration levels equally distributed over the low and high linear range. Intraday precision was determined by analyzing five river samples, spiked with the standard PFCs and $^{13}C_4$-PFOS and $^{13}C_4$-PFOA on the same day ($n = 5$). Interday precision was evaluated by determining five replicates per concentration level, on five consecutive days ($n = 25$). Accuracy was evaluated by comparing the mean recovery in the five or 25 analyses to the nominal concentration values.

2.5. Characterizations for the crystallized morphology of TMGN and the mixture of TMGN and PFOS

The crystallized morphology of TMGN and the mixture of TMGN and PFOS were determined by S-3000N scanning electronic microscopy (SEM, Hitachi, Tokyo, Japan).

2.6. MALDI-TOF-MS analysis

All analysis of PFCs was accomplished with an Autoflex III (Bruker Doltonics, Germany) MALDI-TOF-MS equipped with a pulsed nitrogen laser (337 nm) at a frequency of 20 Hz. An AnchorChip TM target plate with 384 spots was employed. Ions were desorbed from surfaces of the target plate with laser energies of about 75 μJ per pulse. The extraction delay time was optimized to 180 ns. The measurements were performed in negative ionization reflection mode for quantitative analysis. Each mass spectrum was typically summed with 2000 laser shots after being externally calibrated by using PEG-600 sulfate for m/z range from 100 to 1200 Th in the negative ion mode. Negative ion collision-induced dissociation (CID) spectra of PFCs were obtained by MALDI-TOF-MS to identify the chemical structure of PFCs. All mass spectra were analyzed by Flex Analysis software provided by Bruker Doltonics Cop. 5 mg/mL α-cyano-4-hydroxycinnamic acid (CHCA) in 50% acetonitrile containing 0.1% TFA was used as a control matrix.

2.7. LC–MS/MS analysis

LC–MS/MS analysis for PFCs was completed according to that described by Zhang et al. [29]. Briefly, LC separation was performed on a Dionex HPLC system (Sunnyvale, CA). 10 μL of the PFCs extract was injected onto an Acclaim 120 C_{18} column (5 μm particle diameter, 4.6 mm i.d. × 150 mm length, Dionex). Methanol (A) and a deionized water solution containing 50 mmol L^{-1} ammonium acetate (B) were used as mobile phase, and were delivered with flow-rate of 1.0 mL/min. The gradient started at 28% ammonium acetate, then ammonium acetate was reduced to 5% at 4 min before being returned to the original condition at 7 min. Detection was performed with a tandem mass spectrometer system (API 3200; Applied Biosystems/MDS SCIEX, Foster City, CA) with an electrospray ionization source (ESI-MS/MS) operated in the electrospray negative mode. Multiple reaction-monitoring (MRM) mode was operated for quantification of PFCs.

3. Results and discussion

TMGN is a new superbasic organic base which was firstly synthesized by Raab et al. in 2002 [30] (Fig. 1A). Like DMAN (a classical "proton sponge" compound, which was introduced by Alder [31] and was used as the matrix for fatty acids detection and metabolomics studies by MALDI-MS [32,33]), TMGN is regarded as a "proton sponge". The chemical structure of DMAN is shown in Fig. 1B. TMGN has high basicity constant (pK_{BH^+} (MeCN) 25.1) and strong UV absorption at 330–350 nm, which are extremely necessary for a MALDI matrix to assist acidic analytes desorption and deprotonation. Furthermore, TMGN is more resistant to hydrolysis and is a weaker nucleophile towards the alkylating agent in comparison to DMAN. So we assumed that TMGN may also be used as a matrix for acidic PFCs (or other acidic small molecules) analysis by MALDI-TOF-MS.

3.1. Validation of TMGN as a matrix for PFCs analysis

To demonstrate the feasibility of TMGN as a matrix for acidic PFCs analysis, 5 μL of PFOS (1 nmol/μL) standard solution was mixed with equal molar of TMGN in methanol, and 1 μL of the mixture was spotted on the MALDI target plate, dried at room temperature, then detected by MALDI-TOF-MS. We found that only deprotonated ion of PFOS at m/z 499.2 was observed without any matrix interference signals in negative ion mode (Fig. 2A). Meanwhile, in positive ion mode of MALDI-TOF-MS, only protonated ion of TMGN at m/z 355.7 was detected, also without any other interference signals (Fig. 2B). Using DMAN as the matrix, the similar results without interfering ions were also obtained (data was not shown). As we known, DMAN had been used as a matrix for fatty acid analysis by MALDI-TOF-MS [26] but has not been used for environmental analysis till now, and the Acid–Base Driven Concept which was further validated by a combination of MS, NMR, and X-ray experiments and supported by density functional quantum chemical calculations, was introduced to describe the rationale for DMAN as the matrix for acidic compounds detection [33]. As the chemical property of TMGN is similar to that of DMAN, we believe that Acid–Base Driven Concept could also be applied to illuminate the rationale of TMGN as the matrix for PFOS detection by MALDI-TOF-MS. That is to say, PFOS is a very strong acid ($pK_a \ll 1$) and TMGN is a strong organic base; acid–base ion pair of PFOS and TMGN formed after TMGN was mixed with PFOS; during the stage of gas phase ionization, TMGN working as a "proton sponge" which adsorbed any available protons, could take up the proton of PFOS, then, protonated TMGN ions and deprotonated PFOS ions formed simultaneously and could be detected separately in positive and negative ion modes of MALDI-TOF-MS (the illustration is shown in Fig. 2).

As a control experiment, the conventional matrix, α-cyano-4-hydroxycinnamic acid (CHCA) was used to detect PFOS in negative ion mode. The result is shown in Fig. 3A and C. Obviously, a lot of matrix ions were observed in the mass spectrum (peeks denoted by"*" represent the matrix ions of CHCA), and the ion signal of PFOS was suppressed by the matrix ions and could only be found by amplifying the spectrum. However, in the mass spectrum of PFOS with TMGN as the matrix (shown in Fig. 3B and D), only the peek of deprotonated PFOS at m/z 499.2 was found without any other matrix ions interference. All of these results led us to conclude that TMGN was superior to conventional matrix, and was suitable to work as the matrix for PFOS analysis by MALDI-TOF-MS.

Furthermore, the morphology of TMGN and the mixture of TMGN and PFOS after crystallization on the plate were confirmed by using SEM (Fig. 4). It was found that the well-distributed crystals of TMGN (Fig. 4A) and the mixture of TMGN and PFOS (Fig. 4B) were separately formed after drying at room temperature. The excellent surface coverage of the crystals can avoid "sweet spot" phenomena of other matrices like DHB, so TMGN is suitable for quantitative detection of the analytes.

In order to test whether TMGN is suitable to work as the matrix for other acidic PFCs, PFOA, PFNA, PFDA, potassium salts of PFBS, and PFHxS were also selected and mixed with TMGN, respectively.

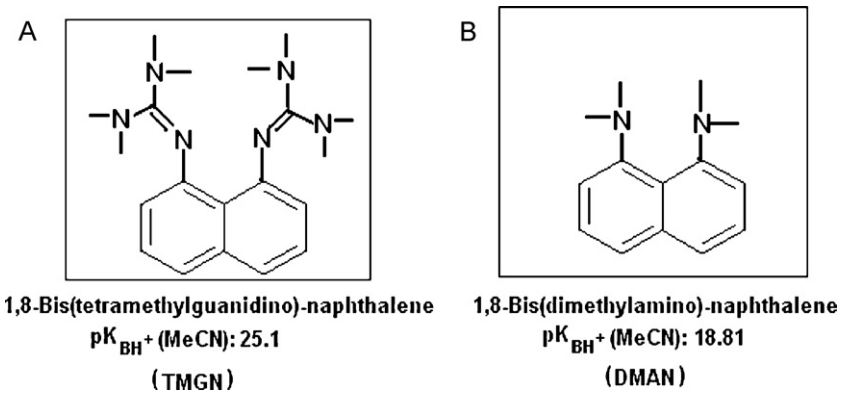

Fig. 1. Chemical structure of TMGN (A) and DMAN (B).

The sample preparation and MALDI-TOF-MS analysis were carried out according to the Section 2 mentioned. The results are shown in Fig. 5. Clear signals of acid anions were obtained for all above-mentioned acidic PFCs. Only deprotonated ions of PFOS at *m*/*z* 499.2, PFHxS at *m*/*z* 399.4, PFBS at *m*/*z* 299.2 were observed, respectively in each mass spectrum, and no matrix ions were found (Fig. 5A–C). In the case of PFOA, besides the peak of deprotonated ions at *m*/*z* 413.5 $[M-H]^-$, the peaks at *m*/*z* 369.4 and 331.4 were also detected in the mass spectrum, which might be assigned for the neutral loss ion $[M-COOH]^-$ and the radical ion after loss of •F $[M-COOH-2F]^-$, respectively (Fig. 5D). In the mass spectra of PFNA and PFDA, the deprotonated ions of PFNA and PFDA were also found at *m*/*z* 463.9 and 513.6, respectively. Moreover, the neutral loss ion of PFNA at *m*/*z* 419.7 $[M-COOH]^-$, the radical ion of PFNA after loss of •F at *m*/*z* 444.9 $[M-H-F]^-$, and the neutral loss ion of PFDA at *m*/*z* 469.5 $[M-COOH]^-$, the radical ion of PFDA after loss of •F at *m*/*z* 494.6 $[M-H-F]^-$, were also detected (Fig. 5E and F). This indicates that partly fragmentation of perfluoroalkyl carboxylic acids occurred in the process of laser desorption. Also, there was no matrix ions interference in all mass spectra of the tested perfluoroalkyl carboxylic acids. All these results suggest that TMGN is an excellent matrix with notable feature of no matrix ions interference in the low mass range (<1000 Da), and is suitable for acidic PFCs analysis by MALDI-TOF-MS, especially for the analysis of perfluoroalkyl sulfonates.

3.2. The sensitivity of MALDI-TOF-MS for PFOS detection

TMGN has higher basicity than DMAN. The higher basicity of TMGN may lead to higher sensitivity for acidic PFCs detection by MALDI-TOF-MS. To test this hypothesis, TMGN and DMAN were separately used as the matrices for directly detecting PFOS with different concentrations (100, 10, 1 ng/mL, 500, 100 pg/mL) in methanol, and 5 replicate measurements were performed for each detection. The results indicate that instrumental LOD of PFOS was 100 pg/mL (signal-to-noise ratio, S/N = 3) with TMGN as the matrix (n = 5, RSD = 9), as shown in Fig. 6A. However, when DMAN was used as the matrix, the instrumental LOD was 1 ng/mL (n = 5, RSD = 11), as

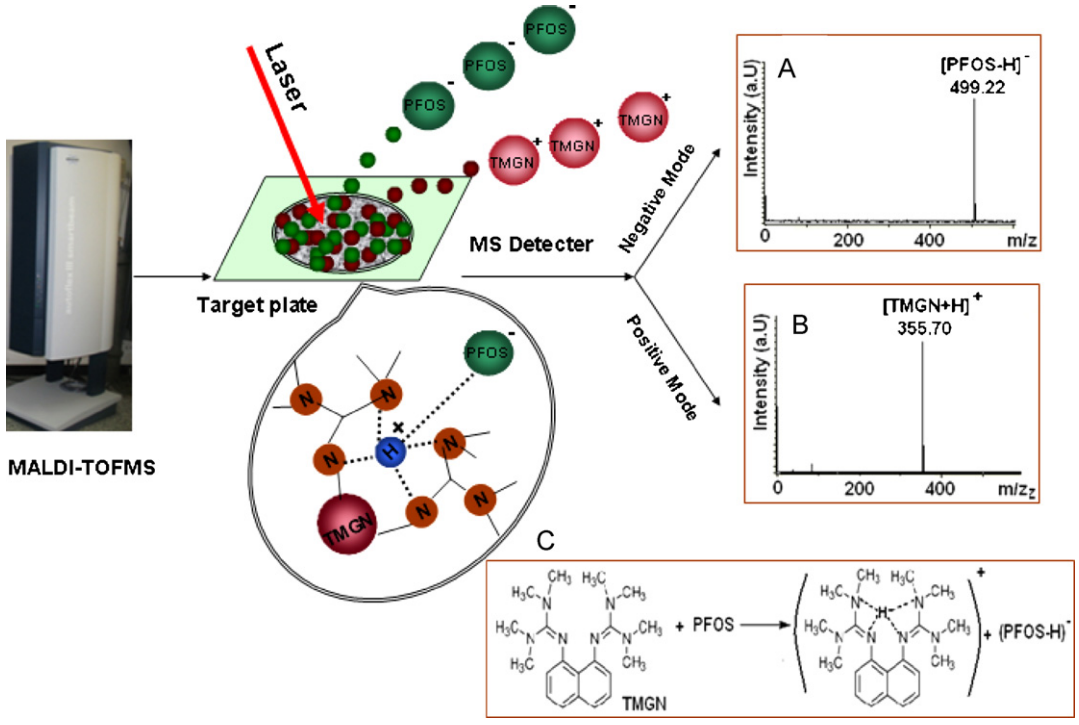

Fig. 2. Schematic illustration of TMGN as matrix for PFOS (*m*/*z* 499.22) analysis by MALDI-TOF-MS. (A) Mass spectrum of 500 pmol of PFOS detected by MALDI-TOF-MS in negative ion mode. (B) Mass spectrum of 500 pmol of PFOS detected by MALDI-TOF-MS in positive ion mode. (C) The illustration of interaction between PFOS and TMGN.

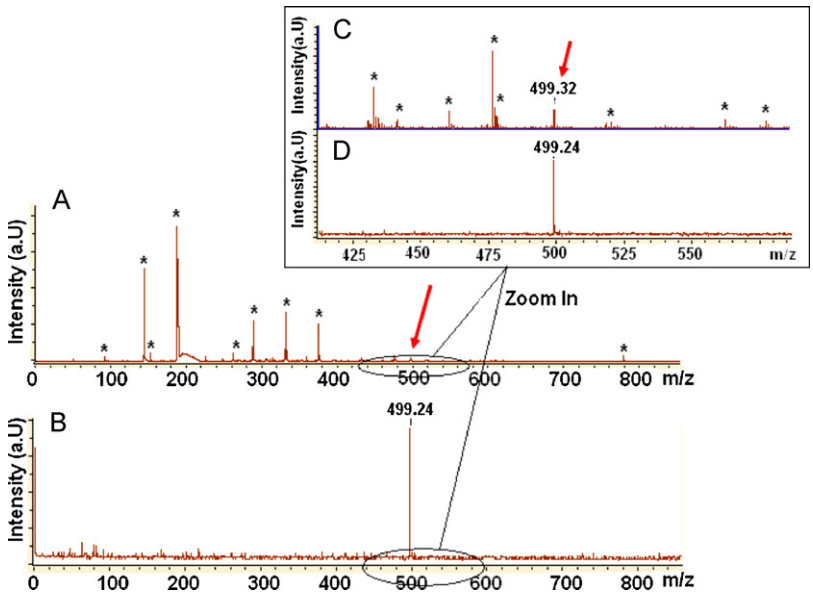

Fig. 3. Mass spectra of 500 pmol PFOS detected by MALDI-TOF-MS with CHCA (A and C) as matrix (peeks denoted by"*" represent the matrix ions of CHCA) and with TMGN (B and D) as matrix.

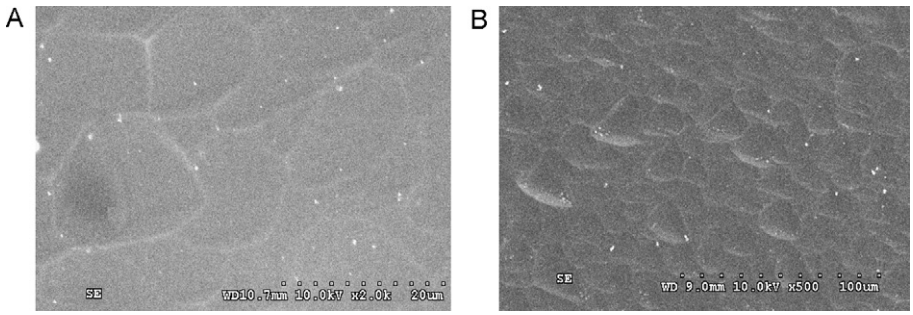

Fig. 4. SEM images of TMGN (A) and the mixture of TMGN and PFOS (4B) after being crystallization on the plate.

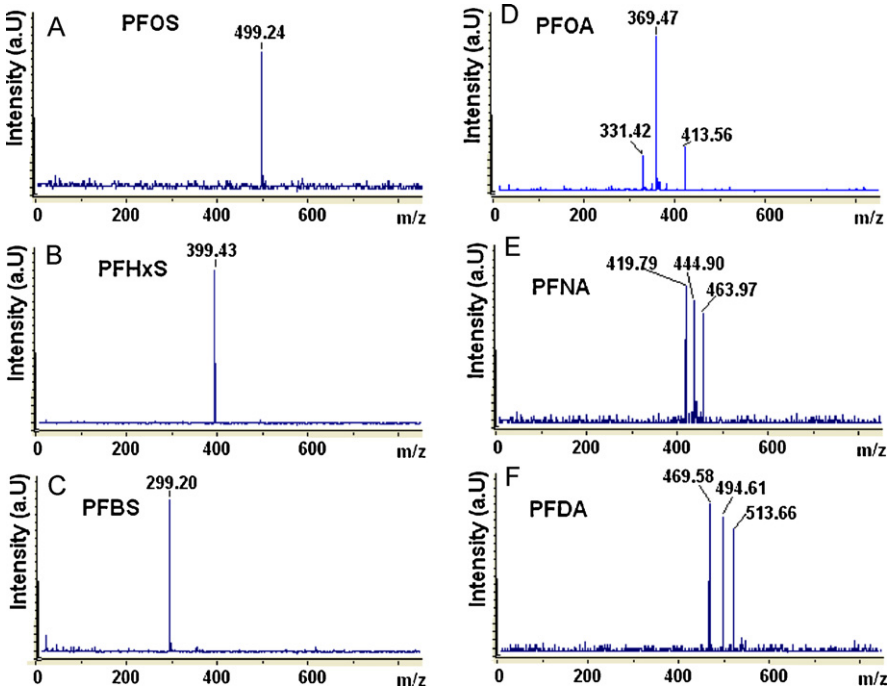

Fig. 5. Mass spectra of acid PFCs detected by MALDI-TOF-MS with TMGN as matrix in negative ion mode. (A) 100 pmol PFOS; (B) 150 pmol PFHxS; (C) 100 pmol PFBS; (D) 150 pmol PFOA; (E) 300 pmol PFNA; (F) 200 pmol PFDA.

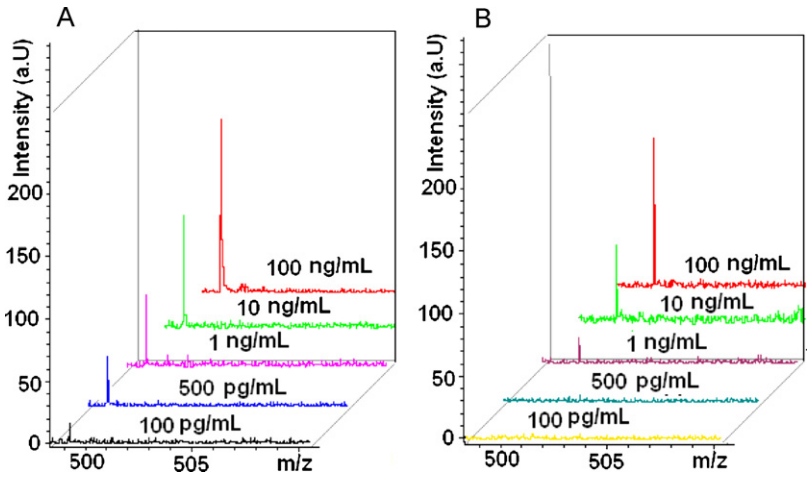

Fig. 6. Mass spectra of different concentration PFOS detected by MALDI-TOF-MS with TMGN (A) or DMAN (B) as matrix.

shown in Fig. 6B. This result suggests that the sensitivity for PFOS detected by MALDI-TOF-MS with TMGN as the matrix is ten-fold higher than that with DMAN as the matrix. We assumed that TMGN is easier to take up the proton of PFOS because of its higher basicity, which may lead to the easier formation of the deprotonated ion of PFOS during the process of laser desorption. It should be noted that TMGN, as the matrix, is more suitable to detect the trace level of PFOS (concentration is lower than 1 ng/mL) than DMAN.

3.3. Validation and application of the method

The potential application of TMGN as the matrix for acidic PFCs analysis in environmental water samples was studied. PFOS, PFHxS, PFBS, PFOA, PFNA, and PFDA were selected as target analytes, and calibration curves were performed with the detection of PFCs by using 500 mL of ultra-pure water (no PFCs contained) spiked with standard PFCs in the range of 0.1–10 ng L^{-1} for PFOS, PFHxS, and PFBS, 0.5–50 ng L^{-1} for PFOA, PFNA, and PFDA. Solid phase extraction (SPE) with C_{18}-SPE cartridge (500 mg, 6 mL) was used as sample pretreatment method to enrich PFCs. 1 ng of the internal standard $^{13}C_4$-PFOS and 5 ng of $^{13}C_4$-PFOA were added prior to extraction. The extraction and cleanup steps were carried out according to Section 2 mentioned. The calibration curves for PFCs were constructed using the internal reference method. The linear range and the correlation coefficient (r) were evaluated and summarized in Table 1. The results indicate that the calibration curves of each target analytes showed a wide linear dynamic range of response (0.1–10 ng L^{-1} for PFOS, PFHxS, and PFBS, and 0.5–50 ng L^{-1} for PFOA, PFNA, and PFDA.), which were over 2 orders of magnitude. The correlation coefficients (r) of the calibration curves are 0.9994, 0.9989, 0.9979, 0.9952, 0.9920, and 0.9907 (n = 7), with detection limits of 0.015, 0.012, 0.010, 0.15, 0.11, and 0.035 ng L^{-1} for PFOS,

Table 1
Analytical parameters of the proposed MALDI-TOF-MS method.

Analyte	Equation	r	RSD (%) (n = 5)	Linear range (ng L^{-1})	Detection limit[a] (ng L^{-1})
PFOS	$y = 0.5653x - 0.0025$	0.9994	6.5	0.1–10	0.015
PFHxS	$y = 0.6531x - 0.075$	0.9989	5.4	0.1–10	0.012
PFBS	$y = 0.7685x + 0.0142$	0.9979	5.2	0.1–10	0.010
PFOA	$y = 0.8745x - 0.0216$	0.9952	7.8	0.5–50	0.15
PFNA	$y = 0.3175x + 0.1005$	0.9920	7.0	0.5–50	0.11
PFDA	$y = 0.7645x - 0.0923$	0.9907	6.2	0.5–50	0.035

[a] The detection limits were calculated by using S/N = 3.

Table 2
The accuracy and precision of the proposed MALDI-TOF-MS method.

Analyte	Conc. level (ng L^{-1})	Intraday (n = 5) recovery % (RSD%)	Interday (n = 25) recovery % (RSD%)
PFOS	0.2	98[a] (11)[b]	89 (14)
	8.0	103 (7)	106 (9)
PFHxS	0.2	101 (9)	98 (5)
	8.0	104 (8)	105 (12)
PFBS	0.2	105 (12)	111 (14)
	8.0	96 (8)	92 (16)
PFOA	0.2	103 (12)	110 (6)
	8.0	94 (7)	91 (11)
PFNA	0.2	92 (12)	109 (12)
	8.0	110 (13)	89 (7)
PFDA	0.2	89 (11)	86 (9)
	8.0	91 (12)	88 (12)

[a] The mean recovery.
[b] The relative standard deviations (RSD%) are given in parentheses.

Table 3
Matrix effect of environmental water samples on the recovery of PFCs in 500 mL water samples spiked with standards of PFCs at two different concentration levels ($n = 4$).

Water samples	PFOS recovery % (RSD% ($n = 4$))	PFHxS recovery % (RSD% ($n = 4$))	PFBS recovery % (RSD% ($n = 4$))	PFOA recovery % (RSD% ($n = 4$))	PFNA recovery % (RSD% ($n = 4$))	PFDA recovery % (RSD% ($n = 4$))
Spiked Concn. at 2 ng L^{-1}						
Deionied water	96 (6)	98 (7)	99 (9)	101 (8)	105 (12)	98 (6)
Tap water	92 (8)	91 (9)	90 (8)	96 (11)	93 (8)	94 (11)
Gaobeidian wastewater	86 (9)	87 (4)	82 (9)	81 (12)	120 (13)	81 (9)
Xiaoqinghe river water	89 (7)	90 (8)	85 (11)	85 (13)	115 (12)	109 (12)
Spiked Concn. at 8 ng L^{-1}						
Deionied water	98 (8)	102 (4)	100 (5)	99 (8)	104 (13)	99 (14)
Tap water	103 (8)	105 (6)	98 (8)	96 (5)	92 (7)	89 (12)
Gaobeidian wastewater	82 (14)	118 (16)	87 (9)	85 (8)	80 (13)	118 (9)
Xiaoqinghe river water	88 (9)	87 (12)	90 (12)	92 (5)	85 (5)	94 (10)

Table 4
Mean concentrations ± standard deviation ($n = 5$) of PFCs detected in real water samples, and the spiked recovery of PFCs obtained by spiking the target analytes.

Water samples	PFOS Background conc. (ng L^{-1}, $n = 5$) [a]Spike recovery (%, $n = 5$)	PFHxS Background conc. (ng L^{-1}, $n = 5$) Spike recovery (%, $n = 5$)	PFBS Background conc. (ng L^{-1}, $n = 5$) Spike recovery (%, $n = 5$)	PFOA Background conc. (ng L^{-1}, $n = 5$) Spike recovery (%, $n = 5$)	PFNA Background conc. (ng L^{-1}, $n = 5$) Spike recovery (%, $n = 5$)	PFDA Background conc. (ng L^{-1}, $n = 5$) Spike recovery (%, $n = 5$)
Detected by MALDI-TOFMS						
Tap water	0.42 ± 0.10	0.58 ± 0.13	nd[b]	0.98 ± 0.12	nd	nd
	102 ± 3	89 ± 5	98 ± 7	86 ± 6	100 ± 5	110 ± 5
Gaobeidian wastewater	3.36 ± 0.07	1.89 ± 0.09	1.56 ± 0.04	8.67 ± 0.10	2.12 ± 0.08	1.81 ± 0.09
	89 ± 6	84 ± 4	86 ± 11	68 ± 8	78 ± 8	69 ± 5
Xiaoqinghe river water	1.12 ± 0.08	0.85 ± 0.08	nd	32.9 ± 0.12	0.891 ± 0.10	0.791± 0.12
	92 ± 5	86 ± 5	107 ± 5	79 ± 5	82 ± 12	78 ± 6
Detected by LC–MS/MS [29]						
Tap water	nd	na[c]	na	nd	nd	nd
	112 ± 4			88 ± 3	101 ± 4	107 ± 3
Gaobeidian	3.22 ± 0.02	na	na	8.33± 0.06	2.05± 0.05	1.89± 0.02
Wastewater	65 ± 6			94 ± 6	84 ± 5	56 ± 2
Xiaoqinghe river water	0.96 ± 0.06	na	na	32.4 ± 0.	0.958± 0.07	0.760± 0.07
	63 ± 2			90 ± 8	79 ± 7	62 ± 7

[a] Recoveries obtained by spiking with the target analytes (1.0 ng L^{-1}).
[b] Not detected.
[c] Not analyzed.

PFHxS, PFBS, PFOA, PFNA, and PFDA, respectively (calculated by using S/N = 3). It should be noted that LOD of PFOS was evaluated as 0.015 ng L^{-1} (calculated by using S/N = 3), which was lower than the LOD (0.036 ng L^{-1}) obtained by LC–MS/MS method reported by Zhang et al. [29].

The precision and recovery data are summarized in Table 2. The result indicates that the intraday precisions for all target PFCs were less than 13%, whereas the interday precisions were less than 16%. The mean recoveries of PFOS ranged from 89% to 106%, the mean recoveries of PFHxS ranged from 98% to 105%, the mean recoveries of PFBS ranged from 92% to 111%, the mean recoveries of PFOA ranged from 91% to 110%, the mean recoveries of PFNA ranged from 89% to 110%, and the mean recoveries of PFDA ranged from 88% to 91%. These data suggest that our proposed method can provide high reproducibility with excellent linearity for PFCs analysis.

Some water samples from different districts of Beijing in China, including tap water, Gaobeidian wastewater, and Xiaoqinghe river water, were collected, and pretreated according to the Section 2. Ultra-pure water and the collected water samples were spiked with standard PFCs at two different concentration levels (2 ng L^{-1} and 8 ng L^{-1}), and 2.0 ng L^{-1} of $^{13}C_4$-PFOS and 5.0 ng L^{-1} of $^{13}C_4$-PFOA were added as internal standards. Then the final samples were extracted by C_{18}-SPE cartridge to investigate the matrix effect on the recovery of the method. The results were compared with each other (Table 3). We found the recoveries of each PFCs in tap water, wastewater and river water samples were slightly lower than those obtained from ultra-pure water samples. However, even for samples with a complex matrix, the recovery of PFCs were still higher than 80% with spiked concentrations at two different levels, so we concluded that the matrix only had a slight influence on the recovery of the method.

The concentrations of the target PFCs in the collected water samples were measured by MALDI-TOF-MS, and the obtained results were compared with the values of the same water samples detected by LC–MS/MS reported by Zhang et al. [29]. The chemical structure of PFCs was identified by negative ion collision-induced dissociation (CID) spectra of PFOS performed by MALDI-TOF-MS. The concentrations of PFCs in different water samples are listed in Table 4. The results indicated that the concentrations of PFOS, PFOA, PFNA, and PFDA in Xiaoqinghe river water samples and Gaobeidian wastewater samples detected by our proposed method are closed to those detected by LC–MS/MS [29]. The concentrations of PFHxS and PFBS were also detected by our method, and the detail can be seen in Table 4. Interestingly, the concentrations of PFOS and PFOA in tap water samples were not detected by LC–MS/MS but were detected by our proposed MALDI-TOF-MS method (0.42 ± 0.10 ng L^{-1} for PFOS and 0.98 ± 0.12 ng L^{-1} for PFOA). This may attribute to the higher sensitivity of our method. All the above results indicate that the proposed MALDI-TOF-MS method is reliable and can be used as an alternative method for trace PFCs detection and quantification in environmental water samples.

4. Conclusions

TMGN, a superbasic proton sponge, was firstly employed as a matrix for sensitive detection of acidic PFCs in environmental water samples by MALDI-TOF-MS. Several acidic PFCs were selected as target analytes for testing the feasibility of TMGN as the matrix. Clear spectra of the selected acidic PFCs were obtained without any matrix ions interference. The simplicity of the obtained mass spectra made our method possible to monitor acidic PFCs in complicated environmental water samples. DMAN, another classical proton sponge having been used as the matrix for fatty acid detection by MALDI-TOF-MS, was also used as the matrix for PFOS analysis. The sensitivity for PFOS with TMGN as the matrix is tenfold higher than that with DMAN the as matrix. The main reason for the higher sensitivity may attribute to the higher basicity of TMGN. A novel strategy of SPE sample pretreatment and MALDI-TOF-MS analysis with TMGN as the matrix was developed to detect the concentrations of PFCs in environmental water samples. The results indicate that TMGN is an excellent matrix for acidic PFCs analysis by MALDI-TOF-MS and the proposed strategy in this work can be used as an alternative method to detect the trace level of PFCs in environmental samples.

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