

Optimized Preconcentration Method Using Ionic Liquid Ferrofluid for Ultra-Trace Determination of Cr(VI) in Drinking Water by Inductively Coupled Plasma Mass Spectrometry

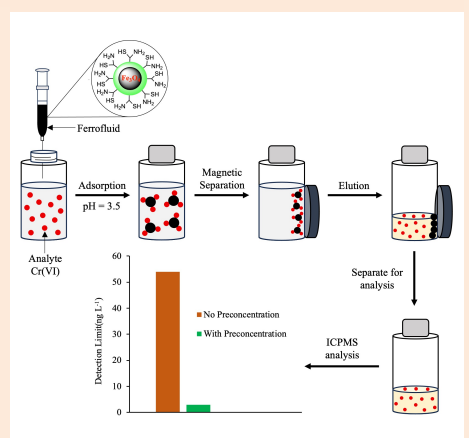
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ABSTRACT: Herein, a simple and fast method was developed for efficient preconcentration of anionic Cr(VI) in drinking water using, for the first time, an ionic liquid ferrofluid (IL-FF) for its interference-free ultra-trace (ng L^{-1}) determination by inductively coupled plasma mass spectrometry. To improve the selectivity of the IL-FF, the surface of commercially available Fe_3O_4 magnetic nanoparticles (MNPs) was coated with silica and functionalized with L-cysteine (SCMNPs-Cys). The structural features of the SCMNPs-Cys were characterized by Fourier transform infrared spectroscopy, scanning electron microscopy with energy dispersive X-ray spectroscopy, and X-ray diffraction. Experimental conditions, including the sample solution pH, elution time, and eluent concentration, were optimized. A 20-fold enrichment factor resulted in a limit of detection of 3 ng L^{-1} . The applicability of the method was confirmed by the analysis of Cr(VI) in different water samples with recoveries of 84–91% ($n=3$).



INTRODUCTION

Toxic and non-degradable potentially toxic elements (PTEs) are released in waters through industrial processes, modern agricultural practices, and inappropriate waste disposal methods.^{1–5} Cr is among these PTEs, with its salts commonly employed in the manufacturing of catalysts, paints, dyes, and fungicides, as well as for leather tanning, photography, ceramic and glass production, chrome plating, chrome alloy and chromium metal production, and corrosion control.^{6,7} The extensive use of Cr across various applications inevitably results in the release of its compounds into water sources.⁸ The presence of PTEs, including Cr, in water poses severe toxicological risks to living organisms.^{4,5}

Cr exists in the environment in two oxidation states, Cr(III) and Cr(VI), exhibiting different toxicity levels.⁹ Trivalent Cr (Cr(III)) is essential for proper functioning of living organisms, whereas hexavalent Cr (Cr(VI)) is toxic, carcinogenic, mutagenic, and

teratogenic.^{6,10,11} The toxicity of Cr(VI) is reported to be 100 times that of Cr(III).¹² Under usual environmental conditions, Cr(III) is slightly soluble in water.^{13,14} Conversely, Cr(VI) exists in water in the form of oxyanions such as CrO_4^{2-} , HCrO_4^{2-} , and $\text{Cr}_2\text{O}_7^{2-}$, depending on the pH (specifically, $\text{Cr}_2\text{O}_7^{2-}$ in strongly acidic solutions and CrO_4^{2-} in alkaline solutions).^{10,15} Cr(VI) anions are highly mobile in below surface environments, remaining unchanged in solution for extended periods of time without being absorbed in soils.^{13,16–19}

The World Health Organization (WHO) has established a guideline value of 0.05 mg L^{-1} for total Cr concentration, while the United States (US) Environmental Protection Agency (EPA) has set a total concentration of 0.1 mg L^{-1} for Cr in drinking water as a “maximum contaminant level goal”.¹⁷ In Canada and the United States, average Cr(VI) levels in drinking water range from $0.2\text{--}2 \mu\text{g L}^{-1}$.²⁰ Following a toxicological review by US EPA and California EPA in 2012, the state established a goal of $0.02 \mu\text{g L}^{-1}$ for Cr(VI) concentration in drinking water with a maximum

contaminant threshold of 0.06 $\mu\text{g L}^{-1}$ to consider “the increased exposure and risk to children”.^{21,22} Hence, determination of Cr(VI) in waters at ng L^{-1} level is important for the protection of public health.

However, even with inductively coupled plasma mass spectrometry (ICPMS), the ng L^{-1} determination of PTEs in environmental samples remains challenging because of spectroscopic interference and matrix effects. Consequently, separation and preconcentration techniques often need to be employed.^{3,23} Several extraction and analytical techniques have been developed for the determination of Cr ions in environmental samples, including precipitation/co-precipitation,²⁴ liquid-liquid extraction,²⁵ solid phase extraction (SPE),^{23,26} dispersive solid phase extraction,¹² magnetic solid phase extraction,²⁷ cloud point extractions,²⁸ and dispersive liquid-liquid micro extraction.²⁹⁻³¹

SPE is widely used for the separation and preconcentration of metal ions because of its simplicity, cost-effectiveness, selectivity, and rapidity, combined with the potential of obtaining high preconcentration factors.³²⁻³⁶ In SPE, a sorbent with a high affinity for the analytes is used as the extracting phase and removal/preconcentration takes place through physisorption and/or chemisorption.⁶ The challenge lies in selecting a sorbent with a high affinity for the analytes. Carbon nanotubes,¹⁶ activated alumina, Amber lite XAD-2000 resin,³⁷ biosorbent,¹⁹ modified silica,³⁸ and magnetic nanoparticles (MNPs)³⁹ have been utilized for the determination of Cr species. Among the above sorbents, MNPs like Fe_3O_4 have attracted significant attention due to their large surface area, low toxicity, simple synthesis, and high adsorption capacity, in addition to their enabling the rapid and easy separation of analyte from aqueous solution using an external magnetic field.⁴⁰ However, these MNPs are not stable under acidic condition, leading to rapid aggregation and poor dispersion in water.⁴¹ Moreover, the very low number of hydroxyl groups on their surface makes them difficult to graft. Suitable surface coating of MNPs and functionalization with organic compounds are essential^{41,42} so that the resulting functionalized MNPs, when dispersed in a carrier liquid, yield a stable ferrofluid that can be utilized for preconcentration.⁴³ A ferrofluid easily disperses upon injection into a sample solution and, because mass transfer is accelerated by the large contact surface between the sample and the sorbent, extraction can occur within a very short period. No centrifugation step is required for phase separation as the ferrofluid can be removed with a magnet.⁴⁴⁻⁴⁶ Different carrier liquids may be used to prepare ferrofluids.⁴⁷⁻⁴⁹ In this regard, ionic liquids (ILs) may replace conventional organic carriers due to their unique physicochemical properties.⁵⁰ Indeed, ILs are very stable compounds, having negligible vapour pressure, low flammability, and the ability to remain in a liquid state over a wide range of temperatures.⁵¹⁻⁵³ Their use as carrier liquid in a ferrofluid reduces the consumption of organic solvents, and thus the associated toxic waste, resulting in a stable and environmentally friendly

ferrofluid.⁴⁷

This work uses an ionic liquid ferrofluid (IL-FF) for the separation and preconcentration of Cr(VI) to enable its interference-free determination at ng L^{-1} level in water samples by inductively coupled plasma mass spectrometry (ICPMS). To achieve this, MNPs are first coated with silica (SiO_2)⁵⁴ and then functionalized with L-cysteine (SCMNPs-Cys). Selective interaction of the SCMNPs-Cys and the target species is expected from the hard and soft acids and bases theory (HSAB theory), as proposed by R. G. Pearson. Indeed, soft bases compounds containing N (such as a nitro or amino group) and S (thiol group) exhibit high selectivity towards anionic forms of Cr(VI), which are typically soft acids.⁴⁴ The interaction between L-cysteine functionalized MNPs with analytes should be stronger than with anionic ions that are hard bases (e.g., SO_4^{2-} , NO_3^{2-} , Cl^- , and MnO_4^-).⁴⁴ To the best knowledge of the authors, this is the first time that such an approach was used for the determination of Cr(VI).

EXPERIMENTAL

Standard Solutions. Multi-elemental standard solutions containing Cr(VI) anions (0, 0.145, 0.435, 0.833, 1.687 and 3.156 $\mu\text{g L}^{-1}$) in 2% (v/v) HNO_3 were used for external calibration. They were prepared daily from dilution of 1000 mg L^{-1} stock solutions in 2% v/v sub-boiled HNO_3 (prepared from chromium (VI) oxide (Cr(VI)) (98%) (Aldrich Chemical Company Inc.) and stored in a refrigerator at 4 °C) using doubly deionized water (DDW) with 18 $\text{M}\Omega$ cm resistivity (Arium Pro UV/DI System, Sartorius Stedim Biotech, Goettingen, Germany). A DST-1000 sub-boiling distillation system (Savillex, Minnetonka, MN, USA) was used to purify ACS grade HNO_3 (Fisher Scientific, Ottawa, ON, Canada). Aliquots of 20 mL of standard solutions were preconcentrated using the IL-FF, followed by elution with 1 mL of 2 M HNO_3 .

Reagents. 1-hexyl-3-methylimidazolium tetrafluoroborate [Hmim] BF_4 (>97.0%), acetic acid (ACS reagent grade, glacial), tetraethyl orthosilicate (TEOS), ammonium hydroxide (reagent grade), ethyl alcohol (95% volume), L-cysteine (98%), and Fe_3O_4 nanoparticles (<40 nm, purity >98%) were purchased from Sigma-Aldrich (St. Louis, MO, USA). A phosphate buffer solution was prepared by dissolving appropriate amounts of sodium dihydrogen phosphate (NaH_2PO_4), and disodium hydrogen phosphate (Na_2HPO_4), also purchased from Sigma-Aldrich. HCl (reagent grade, 36.5-38%), and HNO_3 (ACS reagent grade, 68-70%) were purchased from Fisher Scientific. The vessels were cleaned before use by soaking in 10% (v/v) HNO_3 for at least 24 h and then rinsing thoroughly with DDW.

Instrumentation. A Varian 820MS quadrupole-based ICPMS

Table 1. ICPMS operating parameters

Parameter	Value
Ar plasma gas flow rate (L min ⁻¹)	18
Ar auxiliary gas flow rate (L min ⁻¹)	1.75
Ar sheath gas flow rate (L min ⁻¹)	0.04
Ar nebulizer gas flow rate (L min ⁻¹)	0.98
Sampling position (mm)	6.0
RF power (kW)	1.44
Collision-reaction interface H ₂ (mL min ⁻¹)	65
Sample uptake rate (mL min ⁻¹)	1.0
Monitored analyte (m/z)	⁵² Cr
Dwell time (ms)	10

instrument (Varian Inc., now serviced by Analytik Jena, Jena, Germany) equipped with a collision-reaction interface (CRI) was used in this work. The sample introduction system consisted of a perfluoroalkoxy (PFA) concentric nebulizer, a Peltier-cooled Scott double-pass spray chamber (SCP Science, Baie d'Urfé, QC, Canada), and a manual flow injection manifold consisting of a Cheminert valve (Valco Instruments Co. Inc., Brockville, ON, Canada) equipped with a 100- μ L loop. Additionally, a Nd₂Fe₁₂B magnet was used for separation of MNPs. The instrument operating parameters in Table 1 were used throughout. Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX) were used to determine the morphology, particle size, surface texture, and elemental composition of MNPs. Measurements were made with a Fei Quanta-250 SEM system coupled with an EDX detector. The sample was placed on carbon tape and put under vacuum in the SEM chamber.

Synthesis of MNPs. The synthesis scheme for SCMNPs-Cys is summarized in Fig. S1. Silica coating of MNPs⁵⁵ was done according to a previous study⁵⁶ with some modification using a sol-gel method in basic environment. 4.0 g Fe₃O₄ nanoparticles were dispersed in 200 mL ethanol. The solution was sonicated in a Crest PowerSonic Ultrasonic Cleaner under inert N₂ gas for 20 min. Approximately 0.5 mL of TEOS was then added using a precision pipette, followed by the addition of 35 mL of DDW and 40 mL of NH₄OH. The reaction mixture was sonicated for 2 h under N₂ atmosphere. The solution was then poured into a clean beaker. The silica-coated MNPs (SCMNPs) were separated from solution by placing an external magnet to the bottom of the beaker. The decant was discarded while the SCMNPs were washed with ethanol and DDW at least three times and dried under ambient conditions.

To graft L-cysteine, 4 g SCMNPs were dispersed in 100 mL DDW and sonicated for 10 min under N₂ atmosphere. 50 mL of L-cysteine solution prepared in 0.1 M HCl were then added dropwise while heating at 50 °C in an ultrasonic bath, and the mixture was left to sonicate for 2 h under N₂ atmosphere. The resulting MNPs were washed with water and methanol at least 3 times and dried at room temperature under vacuum. Because the surface of SCMNPs is hydrophilic, L-cysteine could easily bind to

it through the condensation reaction between the -OH groups on the surface of silica and the -COOH groups of L-cysteine.^{57,58}

Preparation and use of ferrofluid. 60 mg of the resulting SCMNPs-Cys and 200 μ L of acetic acid were mixed and heated to 90 °C for 15 min. The acetic acid coated SCMNPs-Cys were dispersed in 100 μ L of [Hmim]BF₄ and sonicated to obtain an IL-FF. This IL-FF was injected into 20 mL sample solution. The resulting cloudy solution was sonicated for 4 min. SCMNPs-Cys were collected using an external magnet. The supernatant liquid was decanted and collected for ICPMS analysis to determine how much analyte was lost during the separation and verify mass balance (Table S1). 1 mL of eluent (2 M HNO₃) was added to the collected SCMNPs-Cys, followed by sonication at 50 °C to desorb analytes. The SCMNPs-Cys were again separated using an external magnet. The eluates were then analyzed by ICPMS using flow injection.

Collection and preparation of water samples. Natural/tap water samples were collected in a 1 L polyethylene bottles. They were acidified to pH 3.5 with distilled HNO₃ and filtered using filter paper. The filtrates were boiled for few min to remove any dissolved gases and subjected to the analytical procedure or stored in the refrigerator at 4 °C.

RESULTS AND DISCUSSION

Different MNPs were tested, including bare Fe₃O₄, Fe₃O₄·SiO₂, Fe₃O₄·SiO₂·TiO₂, Fe₃O₄·SiO₂-MPTMS (3-mercaptopropyltrimethoxysilane), Fe₃O₄·SiO₂-AEAPTMS (N-(2-aminoethyl)-3-aminopropyltrimethoxysilane), and Fe₃O₄·SiO₂-L-cysteine. The best analyte recovery was obtained when Fe₃O₄ MNPs were coated with silica and functionalized with L-cysteine (Fig. S2).

Characterization of functionalized MNPs. The SEM images (Fig. S3) indicate that Fe₃O₄ MNPs were successfully coated. The SEM EDX spectra (Fig. 1) indicate bare Fe₃O₄ (Fig. 1a), the presence of Si after coating with silica (Fig. 1b), and S after grafting with L-cysteine (Fig. 1c). Because N cannot be detected by EDX, Fourier transform infrared (FTIR) spectroscopy was used to confirm the absorption bands of -SH, -NH₂, Fe-O, Si-O, Si-O-Si, and Si-O-H (Fig. 2). The spectra of Fe₃O₄·SiO₂-L-cysteine MNPs exhibit the characteristic adsorption bands of the amino group, the carbonyl group, and the hydrosulphide group of L-cysteine *i.e.*, 1480 cm⁻¹ due to NH bending vibration, 1075 cm⁻¹ from the C-N stretching vibration, 1625 and 1400 cm⁻¹ due to the asymmetric and symmetric stretching of carbonyl group respectively, and the weak band at 2548 cm⁻¹ is from the S-H stretching vibration. Furthermore, a strong adsorption peak at 580 cm⁻¹ is due to the Fe-O stretching vibration of Fe₃O₄. For the final

Fig. 1 SEM EDX spectra of MNPs at different stages of preparation: a) Fe_3O_4 ; b) $\text{Fe}_3\text{O}_4\text{:SiO}_2$; and c) $\text{Fe}_3\text{O}_4\text{:SiO}_2\text{-L-Cysteine}$.

Fig. 2 FTIR spectra of the MNPs at different stages of their preparation.

Fig. 3 Preconcentration factor (PF) achieved using different concentrations of HNO_3 for elution (analyte from 20 mL of $0.45 \mu\text{g L}^{-1}$ Cr(VI) sample solution at pH 3.5 was eluted with 1 mL of HNO_3 solution); expected PF = 20 [n=3].

Fig. 4 Effect of sample solution pH on Cr(VI) adsorption (analyte from 20 mL of $0.45 \mu\text{g L}^{-1}$ Cr(VI) sample solution was eluted with 1 mL of 2 M HNO_3) [n=3].

Fig. 5 Effect of adsorption and elution times on Cr(VI) recovery (analyte from 20 mL of $0.45 \mu\text{g L}^{-1}$ Cr(VI) sample solution at pH 3.5 was eluted with 1 mL of 2 M HNO_3) [n=3].

SCMPNs-Cys, peaks at 580 cm^{-1} , 800 cm^{-1} , 950 cm^{-1} , 1680 cm^{-1} , 1550 cm^{-1} , 2600 cm^{-1} , and 3400 cm^{-1} indicate that Fe_3O_4 is covered by SiO_2 and functionalized with L-cysteine. Based on the X-ray diffraction pattern (Fig. S4), the position and structure of the characteristic peaks do not change during the entire process.

Selection of eluent concentration. To avoid Cl-based spectroscopic interference on Cr, only HNO_3 was considered as eluent. Various HNO_3 concentrations were investigated to elute the adsorbed Cr(VI). The recoveries were highest when using at least 2 mol L^{-1} HNO_3 (Fig. 3). Hence, 2 mol L^{-1} HNO_3 was selected as eluent for the subsequent experiments.

Effect of sample solution pH on adsorption. The pH is the most important operational parameter in the adsorption process, as it influences the surface properties of the sorbent, including its adsorption capacity, and the Cr ionic forms in solution. The effect of pH on the retention of Cr(VI) on SCMPNs-Cys was investigated in the pH range of 1-5, which was adjusted by using phosphate buffer solution, keeping all other parameters constant. Fig. 4 shows that analyte recovery was good when the pH was at least 3.5, which was thus used in subsequent experiments.

Table 2. Comparison of the Cr(VI) detection limit by the proposed method compared to those reported in the literature

Detection techniques	Sorbent	Preconcentration factor	Detection limit (ng L ⁻¹)	Ref.
ICPOES ^a	1.75 Fe ₃ O ₄ @MnO ₂ , Al ₂ O ₃ @AAPTMS ^b	94	30	[64]
SPE-ICPMS	AAPTMS modified MWCNTs ^c	-	38	[44]
SPE-ICPOES	Chelating resin	-	150	[65]
SPE-ICPMS	Meso Al ₂ O ₃ NPs	5	18	[63]
SPE-FAAS ^d	Fe ₃ O ₄ /Cr(VI)- INPs ^e	98	290	[66]
SPE-FAAS	Fe ₃ O ₄ -GO	200	100	[67]
SPE-ICPMS	Fe ₃ O ₄ ·SiO ₂ ·L-cysteine	20	3	This Work

^a Inductively coupled plasma optical emission spectrometry; ^b 3-(2-Aminoethylamino) propyltrimethoxysilane; ^c Multi-wall carbon nanotubes; ^d Flame atomic absorption spectrophotometry; ^e Imprinted nanoparticles.

Table 3. Concentrations (µg L⁻¹) of Cr(VI) measured in artificial and natural waters (average ± standard deviation; n=3) with and without spiking (analyte from 20 mL sample solution at pH 3.5 eluted with 1 mL of 2 M HNO₃) and corresponding recovery

Sample	Added	Found	Added	Found	Recovery (%)
DDW ^a	0	<0.03	0.45	0.41 ± 0.05	91 ± 2
Tap water ^b	0	0.10 ± 0.09	0.45	0.4 ± 0.3	84 ± 1
Mineral water ^c	0	0.05 ± 0.03	0.45	0.4 ± 0.7	86 ± 1

^a Beauchemin Lab; ^b Kingston, ON; ^c purchased from local grocery store.

The adsorption of Cr(VI) may be due to the electrostatic attraction between the anionic Cr(VI) (CrO₄²⁻, HCrO₄²⁻, and Cr₂O₇²⁻) and protonated amine.⁵⁹⁻⁶¹ It decreased at pH > 6 (not shown), likely as a result of competition from hydroxide ions.⁵⁵ This is in good agreement with previous studies on different adsorbents.^{6,59,62,63}

Effect of sorbent mass and of adsorption and elution times. To minimize the time required for sample processing, the ultrasonication times during adsorption and elution of Cr(VI) were studied using the minimum amount of sorbent, i.e. 60 mg, that provided good analyte recovery (Fig. S5). More than 90% adsorption and elution occurred in 4 min and 2 min respectively (Fig. 5), which were thus used in subsequent experiments.

Influence of sample volume. The effect of sample volume was studied using 10 to 200 mL of 0.4 µg L⁻¹ of Cr(VI) (Fig. S6). Almost quantitative recovery was achieved with up to 100 mL of sample solution. However, the extraction efficiency decreased slightly with a larger sample volume. Hence, at most 100 mL of sample solution was used in subsequent experiments.

Analytical performance and sorbent regeneration. Standard solutions containing Cr(VI) (0, 0.145, 0.435, 0.833, 1.687 and 3.156 µg L⁻¹) in HNO₃ were used for external calibration. In each case, 20 mL of standard solution were subjected to the IL-FF preconcentration procedure, and elution was done with 1 mL of 2.0 M HNO₃. Good correlation (R² > 0.992) was obtained. The resulting detection limit (i.e., 3 s_b/m, where s_b is the standard deviation of 10 measurements of method blank and m is the slope of the calibration curve) of 3 ng L⁻¹ for Cr(VI) is lower than that achieved in other studies (Table 2). Due to the high sensitivity of ICPMS, lower detection limits are achieved when ICPMS is used for detection than when less sensitive detectors (ICPOES, FAAS)

are employed. The lower detection limit achieved in this work compared to that expected based solely on the preconcentration

Table 4. Measured concentration (µg L⁻¹) of Cr(VI) in natural waters (average ± standard deviation; n=3) obtained by external calibration compared to that obtained by the method of standard addition (analyte from 20 mL sample solution at pH 3.5 eluted with 1 mL of 2 M HNO₃)

Sample	External calibration	Standard addition
Tap water	0.10 ± 0.09	0.12 ± 0.05
Mineral water	0.05 ± 0.03	0.07 ± 0.04

factor from previous ICPMS-based works likely reflects the inherent high sensitivity of the Varian 820MS, which uses an ion mirror to deflect and focus ions into the quadrupole, combined with a different sample introduction system (affecting the droplet size distribution and sample introduction efficiency). Furthermore, the SCMNP-Cys could be reused three times without a significant loss of analytical performance (Fig. S7). Considering that 4 g of SCMNP-Cys could be prepared in one batch and only 60 mg of SCMNP-Cys was used per extraction, this reusable time is acceptable.

Sample analysis and accuracy. The results from spiking experiments on various water samples are summarized in Table 3; this method provides acceptable recoveries in addition to being rapid for the selective determination of Cr(VI) in drinking waters. The higher concentration of Cr(VI) in tap water than in mineral water suggests that chlorine in tap water may readily oxidize Cr(III) to Cr(VI). In any case, the accuracy of this method was assessed through comparison of the results obtained by external calibration and by standard addition. The good agreement between the results of the two calibration strategies (Table 4) indicates that the method is accurate and useful for real sample analysis.

CONCLUSION

This study focused on developing a new method to separate and preconcentrate Cr(VI) for its interference-free determination in drinking water at the ng L^{-1} level by ICPMS. For the first time, L-cysteine functionalized and silica-coated MNPs were successfully synthesized by a sol-gel method with the assistance of sonication and used as an adsorbent in IL-FF for the separation and preconcentration of anionic Cr(VI) in aqueous solution. An ionic liquid, [Hmim]BF₄, was used as carrier solvent to provide a stable and environmentally friendly ferrofluid. In comparison to other SPE extraction methods, the proposed method is much faster due to the high dispersibility of the sorbent in the aqueous phase and the simple phase separation using an external magnet. In addition to being selective and reproducible, the sorbent enables fast adsorption and good regeneration, making it safer, greener, and economical compared to other approaches. Compared to previous separation and preconcentration procedures for Cr(VI), this method also provides a lower detection limit for Cr(VI). It is thus advantageous for the routine measurement of Cr(VI) at ng L^{-1} levels in drinking water or environmental samples. Future work will involve the analysis of certified reference materials to validate the method. Furthermore, the effect of potentially interfering co-existing ions will also be studied. Finally, the approach will be extended to the adsorption/preconcentration of other anionic PTEs in water.

ASSOCIATED CONTENT

Supporting information (Table S1 and Figs. S1-S7) is available at www.at-spectrosc.com/as/home.

AUTHOR INFORMATION



Diane Beauchemin received her Ph.D. in 1984 from Université de Montréal. She is a professor (Full) at Queen's University. Her research efforts are focused on inductively coupled plasma mass spectrometry (ICPMS) and ICP optical emission spectrometry (OES) from both fundamental and application perspectives, and expanding the range of application of ICPMS/OES to geochemical exploration, risk assessment of food safety, characterization of nanoparticles, and forensic analysis. She has been working as member of editorial board for *Atomic Spectroscopy*. Diane Beauchemin won the Alan Date Memorial Award (1988) from VG Elemental, the Distinguished Service Award (2001) from Spectroscopy Society of Canada, the Maxxam Award (2017) and Clara Benson Award (2019) from Canadian Society for Chemistry, and the Gerhard Herzberg Award (2018) from the Canadian Society for Analytical Sciences and Spectroscopy. She is author or co-author of over 160 articles published in peer-reviewed scientific journals.

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Notes

The authors declare no competing financial interest.

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