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Analysis of Volatile Methylsiloxanes in Water using a Small-scale Liquid-liquid Extraction Method followed by Gas Chromatography-mass Spectrometry (LLE-GC-MS)

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Abstract

Volatile methylsiloxanes (VMS) are ubiquitous anthropogenic pollutants that have been under scrutiny for their potential toxicity and environmental persistence. The aim of this work was to develop and validate a fast and reliable methodology to determine seven VMSs (D3, D4, D5, D6, L3, L4 and L5) in water matrices, based on a small-scale liquid-liquid extraction (LLE) assisted by ultrasounds and using a low volume of organic solvents. VMSs were quantified by gas chromatography-mass spectrometry (GC-MS). This methodology was successfully validated, showing low detection limits and a good precision (most of the relative standard deviations values below 15%) and accuracy (53-108%). Wastewater samples were analyzed and D5 and D6 were the dominant compounds in influent streams, with similar concentrations to those found in literature (up to 7 µg L^{-1}). Most effluent samples presented VMSs levels below the limits of detection, with only D5 reaching up to 0.05 µg L^{-1}.

Author Keywords. Volatile Methylsiloxanes, Wastewater, Gas Chromatography – Mass Spectrometry.

Type: Research Article

1. Introduction

Volatile methylsiloxanes (VMSs) are a group of compounds characterized by a linear (Ln) or cyclic (Dn) Si-O backbone saturated with methyl groups, with “n” representing the number of silicon atoms (Lassen et al. 2005). They can be considered emergent compounds and are widely used in several industrial and domestic applications, particularly in the formulations of personal care products (PCPs), such as skin and hair care products, soaps, perfumes and fragrances, antiperspirants, sunscreens, balms or make-up (Rücker and Kümmerer 2015).

According to the latest report by International Market Analysis Research and Consulting group, the global siloxanes market reached a volume of 2.4 million tons annually (IMARC Group 2020). Europe is considered the largest market for cosmetics and PCPs in the world, valued at €78.6 billion euros. The majority of Europe’s 500 million consumers use cosmetics and PCPs every day to protect their health, enhance their well-being and boost their self-esteem (Cosmetics Europe 2019). With the increase in production and usage, concerns about environmental emissions of VMSs and consequent human exposure are increasing (Xu et al. 2012; Xu et al. 2015). The congeners D4, D5, and D6 have been classified as high production volume chemicals by the US Environmental Protection Agency (OECD 2007; USEPA 2007) and are the most studied VMSs. Their concentrations in PCPs from different countries have already been summarized in some studies, with the highest concentrations found in antiperspirants, liquid foundations and sunscreens, reaching up to 686 mg g^{-1} (Tran et al. 2019). Consequently, several environmental protection organizations worldwide have been concerned about the significant emissions of VMSs to the environment and their risks to human health (Environment Canada and Health Canada 2008a, 2008b, 2008c; Environment Agency 2009a, 2009b, 2009c; USEPA 2014). Their continuous release coupled with their low rate of degradation may result in a net accumulation. It is estimated that around 90% of VMSs present in PCPs are volatilized during use, with the remaining 10% being discharged down-the-drain to the sewage systems (Montemayor, Price, and van Egmond 2013). Although some part may be lost by volatilization during each stage of treatment in wastewater treatment plants (WWTPs), the rest will accumulate on sludge or be discharged through the final effluent (Alleni, Kochs, and Chandra 1997; Montemayor, Price, and van Egmond 2013).

WWTPs effluents are usually discharged to a surface water body (aquatic ecosystem), making them the main source of numerous contaminants to the environment, which can potentially cause risks to ecological receptors. This may result in the direct exposure of aquatic receptors and benthic invertebrates through the contact and/or ingestion of sediments, and indirect exposure through the aquatic food chain (Nusz et al. 2018). Some studies have revealed that VMSs are potentially toxic to living organisms, since at high doses they affect the reproductive systems of animals, are carcinogenic, and harm the respiratory tract (Tran et al. 2019).

Being ubiquitous compounds, some problems have been identified during the detection and quantification of VMSs at trace levels. Background contamination (indoor air of laboratories) and their presence in different materials (*e.g.,* GC columns and inlet septa, lubricants used in glassware and vacuum systems, O-rings, pump fluids, caps and tubing) are some examples. Therefore, it is essential to develop protocols that minimize external contaminations and quality assurance/quality control (QA/QC) procedures to demonstrate the performance of the analysis. Moreover, the critical point in the determination of VMSs in wastewater samples is the extraction method, which may also include the clean-up and pre-concentration of the samples. These steps are usually laborious, very time-consuming and use high amounts of solvents. This is the case of liquid-liquid extraction (LLE), one of the most frequently applied technique to analyze VMSs in wastewater (Xu et al. 2017; Li et al. 2016; Sanchís et al. 2013; Bletsou et al. 2013). Literature also indicates that most studies regarding the determination of VMSs in water samples are based on gas chromatography-mass spectrometry (GC-MS) analysis (Capela et al. 2017).

To develop a smaller scale LLE-GC-MS method to determine these trace-level compounds in wastewater samples was the main objective of this work, using a quicker and "greener" extraction approach (Gałuszka, Migaszewski, and Namieśnik 2013), since less solvent volumes are applied. The method validation parameters were determined, including the linearity, limits of detection and quantification, precision, and accuracy. Naturally-contaminated wastewater samples were analyzed in order to prove the applicability of the developed method and to confirm the occurrence of these compounds in the environment.

2. Materials and Methods

2.1. Reagents and materials

Seven VMSs (D3, D4, D5, D6, L3, L4 and L5) were used in the experiments. Individual linear (L3-L5) and cyclic (D3-D6) VMSs and the internal standard used, tetrakis(trimethylsilyloxy) silane (M4Q), were purchased from Sigma-Aldrich (St. Louis, MO, USA) with a purity >97%. From these standards, individual stock solutions at 1.0 g L^{-1} were prepared in *n*-hexane (≥ 95% from VWR, Fontenaysous-Bois, France). From those, mix stock solutions of 0.5 and 2.5 mg L^{-1} containing all the target analytes were prepared in acetone. A diluted M4Q individual stock solution, with a final concentration of 5 mg L^{-1}, was also prepared in acetone (≥ 99.8% from Merck, Darmstadt, Germany). All the solutions were stored at - 20 °C in the absence of light. Helium (99.999%) used in the GC-MS system and nitrogen (99.999%) for solvent evaporation, were supplied by Air Liquide (Maia, Portugal).

2.2. Samples

To evaluate the applicability of the proposed method, the extraction of VMSs was performed in ten wastewater samples (5 influent samples and 5 effluent samples) collected in August 2021 from a Portuguese WWTP. These were composite samples, collected every 6 h during 24 h, using wide-mouth 500 mL high-density polyethylene (HDPE) bottles with a rigid polypropylene (PP) double-seal closure, designed to prevent leakage. All samples were stored in the dark at -20 °C until they were processed in duplicate for analysis.

2.3. Extraction procedure

First, 30 mL of water sample were added to a 50 mL conical centrifuge tube. A volume of 25 µL of internal standard (M4Q) of the 5 mg L^{-1} solution was then included (125 ng). The sample was vortexed for 10 seconds to homogenize and left to stabilize for 30 minutes. Then, 10 mL of *n*-hexane (extraction solvent) was added, and the mixture was vortexed for 5 min, sonicated for 10 min in an ultrasound bath (200 Watts) and centrifuged for 5 min at 2760 *g*. The supernatant was transferred to a 12 mL amber vial and the volume reduced to 1 mL under a gentle stream of N_2. Then, it was transferred to an amber glass microvial, through successive washes with *n*-hexane. Finally, the extract was reduced to 500 µL under N_2 and quantified by GC-MS. A scheme of the extraction procedure is presented in Figure 1.

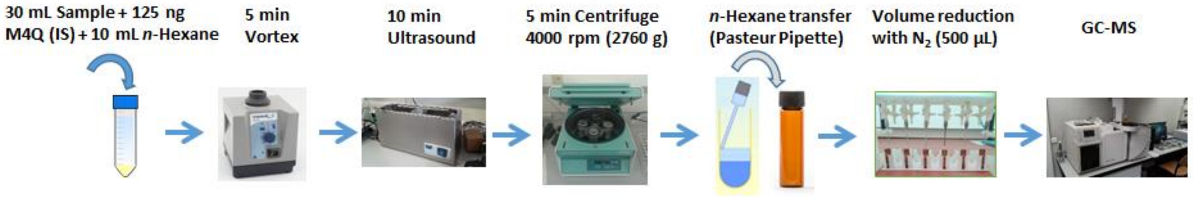

Figure 1: Extraction procedure based on small scale liquid-liquid extraction followed by gas chromatography-mass spectrometry analysis

2.4. Instrumental analysis

The extracts were analyzed using a Varian Ion Trap GC–MS system (Walnut Creek, CA, USA), equipped with a 450-GC gas chromatograph, a 240-MS ion trap mass spectrometer, a CP-1177 split/splitless injector, adapted with a Merlin Microseal System and an autosampler model CP-8410. The mass spectrometer was operated in the electron ionization (EI) mode (70 eV). The separation was obtained at a constant flow of helium, with a purity of 99.999% (1.0 mL min^{-1}), using a low-bleed Agilent DB-5MS ultra-inert column (30 m x 0.25 mm x 0.25 µm). The oven temperature was programmed as follows: initially at 35 °C for 5 min, followed by successive increases of 10 °C min^{-1} until 95 °C, of 5 °C min^{-1} until 140 °C, and of 35 °C min^{-1} until 300 °C and kept for 5.5 min - total time of analysis of 30 min. One µL was injected in splitless mode (200 °C), followed by a 100:1 split after 1 min. The temperatures of the manifold, ion trap, transfer line and injector were 50, 200, 250 and 200 °C, respectively, and the filament emission current was 50 µA. For the quantitative analysis of target compounds, selected ion storage (SIS) mode was applied. The identification of the target compounds was based on the retention times and the relative abundance of the monitored ions (Table 1), with the quantifier ions in bold. A chromatogram of a 150 µg L^{-1} VMSs standard, with all compounds analyzed in SIS mode, is presented in Figure 2.

Segment Description		Identification and Quantification Parameters		
Time Range (min)	**Mass Ranges (m/z)**	**Target Compound**	**Retention Time (min)**	**Qualifier and Quantifier Ions (m/z)**
0.00-6.00	Ionization off			
6.00-8.00	132-134, 190-192, 206-210	D3	7.43	133, 191, **207**
8.00-9.50	72-74, 130-134, 220-224	L3	8.89	73, 133, **221**
9.50-12.00	191-194, 264-268, 280-284	D4	11.19	193, 265, **281**
12.00-13.00	190-194, 206-210, 294-279	L4	12.66	191, **207**, 295
13.00-14.70	248-251, 266-270, 354-358	D5	14.45	251, **267**, 355
14.70-17.00	146-150, 280-284, 368-371	M4Q	15.19	147, **281**, 369
		L5	16.57	147, **281**, 369
17.00-20.00	324-328, 340-344, 427-431	D6	18.48	325, **341**, 430
20.00-30.00	Ionization off			

Table 1: SIS mode parameters for detection and quantification of VMSs by GC-MS

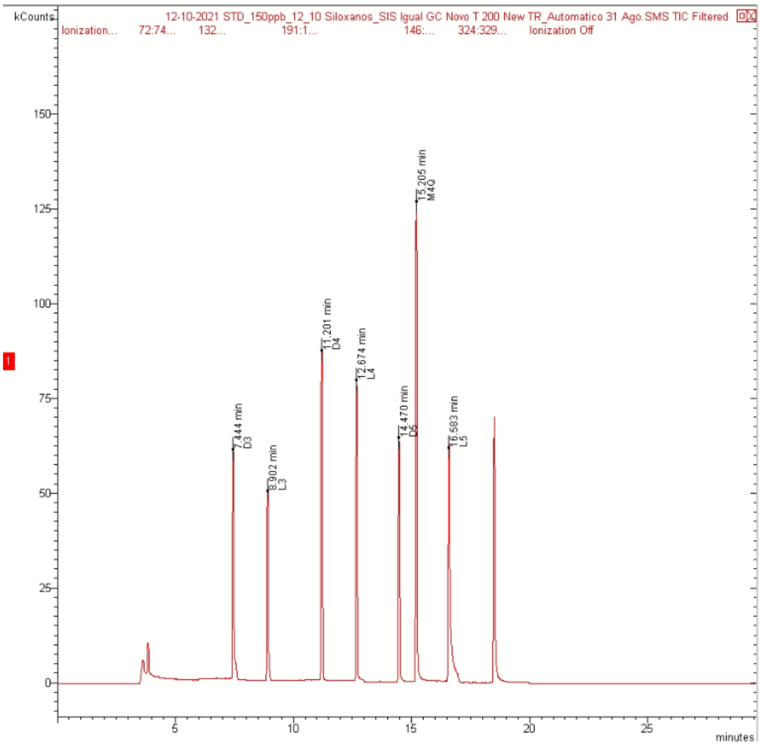

Figure 2: SIS mode chromatogram of a 150 µg L^{-1} VMSs standard (250 µg L^{-1} M4Q – Internal Standard) in *n*-hexane

2.5. Quality assurance/Quality control

Due to the VMSs ubiquity, analysts in the laboratory avoided the use of PCPs containing VMSs such as make-up, deodorants, body and hand creams/lotions and powder-free nitrile gloves were switched whenever handling different samples. All glassware was previously subjected to a special cleaning and decontamination procedure, by pre-rinsing with acetone and distilled water, with non-volumetric items subsequently baked at 400 °C for at least 1 hour. Sample manipulation was reduced to a minimum and performed in a clean air chamber. To reduce possible GC-MS sources of siloxanes from injector septa and capillary columns, a septumless Merlin Seal was adapted to the injector and a low-bleed column was used for target compound separation. Procedural blanks were analyzed in every extraction batch. When necessary, blank values were subtracted from all the concentrations reported. Chromatographic blanks (injection of pure solvent) were also performed, but no memory effects were observed. To remove any residual material from the injections, the chromatographic runs were programmed with a final clean-up step, in which the GC column was heated to 300 °C and kept for 5 min.

3. Discussion

3.1. Method validation

The method was validated based on the procedure described by EURACHEM/CITAC Guide (Magnusson and Örnemark 2014). The parameters included the determination of linearity, instrumental limit of detection (IDL) and quantification (IQL), method limits of detection (MDL) and quantification (MQL), precision and accuracy, and are described in Table 2, Table 3 and Table 4.

Linearity was assessed by the direct injection of nine standards, prepared in *n*-hexane, containing all the VMSs at concentration levels ranging from 7.5 to 1200 μg L^{-1}. Calibration curves were obtained by correlating the mass ratio of each target and the internal standard (mass target compound/mass internal standard) with the response factors (RF = Peak area target compound/Peak area internal standard). All analyzed compounds showed a linear behavior within this range, with $R>0.9998$.

The instrument detection limit (IDL) was estimated by determining the injected mass at which the analytes peaks produced a signal-to-noise ratio (S/N) of 3, while the instrument quantification limit (IQL) a S/N of 10. Therefore, they were assessed using the calibration standard of lowest concentration (1 μL injection). The method detection limits (MDL) and quantification limits (MQL) were also calculated based on a $S/N = 3$ and $S/N = 10$, respectively. They were assessed by the injection of spiked wastewater samples (influent and effluent). The IDL ranged from 0.01 pg (D5) and 0.24 pg (L3), while the MDL ranged from 0.2 ng L^{-1} (D5) to 67.5 ng L^{-1} (L3).

Precision (intra-day and inter-day) and accuracy (recovery tests) were evaluated by spiking wastewater samples (influent and effluent) in triplicate and at two different concentration levels (2.5 and 10 μg L^{-1}). Good precision was obtained since most of the relative standard deviation's values (RSD) were below 15%. Recoveries in influent and effluent ranged between 53% and 108%, except for D3 and L3, with recoveries between 16 and 30%. These lower values for D3 and L3 may be due to volatilization losses (since they are the compounds with lower boiling points). Internal standard (M4Q) recoveries ranged from 64 to 73%.

Compound	**Linearity Range (μg L^{-1})**	**R**	**IDL (pg)**	**IQL (pg)**	**Influent**		**Effluent**	
					MDL (ng L^{-1})	**MQL (ng L^{-1})**	**MDL (ng L^{-1})**	**MQL (ng L^{-1})**
L3	7.5 - 1200	0.9998	0.24	0.79	67.5	224.9	58.4	194.6
L4		0.9999	0.02	0.06	3.4	11.3	5.6	18.6
L5		0.9999	0.18	0.60	4.3	14.4	5.3	17.5
D3	7.5 - 1200	0.9999	0.18	0.59	63.5	211.6	49.0	163.4
D4		0.9998	0.06	0.21	5.8	19.4	7.2	24.1
D5		0.9999	0.01	0.02	0.2	0.7	0.9	2.9
D6		0.9998	0.04	0.14	1.7	5.8	4.0	13.4

Table 2: Linearity range (direct injection) and limits of detection and quantification for VMSs analysis by LLE-GC-MS

Compound	**Intra-day precision (%RSD, n=4)**				**Inter-day precision (%RSD, n=3)**			
	Influent		Effluent		Influent		Effluent	
	2.5 μg L^{-1}	10 μg L^{-1}	2.5 μg L^{-1}	10 μg L^{-1}	2.5 μg L^{-1}	10 μg L^{-1}	2.5 μg L^{-1}	10 μg L^{-1}
L3	16	9	10	7	13	24	9	17
L4	7	2	4	6	22	14	1	4
L5	4	2	5	2	31	17	8	6
D3	17	3	6	4	43	19	2	15
D4	23	12	4	6	37	28	8	12
D5	6	5	7	1	21	28	9	8
D6	4	1	6	3	24	22	4	6

Table 3: Precision of the proposed methodology

Compound	**Accuracy (%RSD, n=4)**					
	Influent		Effluent		Influent Mean	Effluent Mean
	2.5 μg L^{-1}	10 μg L^{-1}	2.5 μg L^{-1}	10 μg L^{-1}		
L3	23	25	22	25	24 ± 1	24 ± 2
L4	65	68	53	62	66 ± 2	58 ± 6
L5	93	93	100	93	93 ± 0	96 ± 5
D3	47	13	20	13	30 ± 24	16 ± 5
D4	104	69	75	49	87 ± 25	62 ± 18
D5	108	94	85	81	101 ± 10	83 ± 3
D6	77	94	92	94	85 ± 12	93 ± 1

Table 4: Accuracy of the proposed methodology

3.2. Method comparison with literature

A comparison between the proposed approach and traditional LLE studies published in literature was conducted, as presented in Table 5. Traditional LLE presents several disadvantages: is very time consuming, often including multiple extractions, requires high volumes of sample and high volumes of toxic extractants and the use of separatory funnels, which hinders the analysis of a large amount of samples per day. In the development of this "greener" procedure, an effort was made to diminish sample manipulation and use of other type of equipment/materials, in order to decrease any potential sample contamination and analyte loss. The main benefits of the proposed methodology compared to others are: a) lower sample and extraction solvent volumes; b) lower cost (one 2.5 L *n*-hexane bottle = 250 sample extractions); c) faster and more environment-friendly extraction approach.

In terms of sample volume, the developed method only requires 30 mL of sample, while others use between 100 mL and 1 L. It also comprises only one extraction step with 10 mL of *n*-

hexane, while others use mixtures of solvents (*n*-hexane with ethyl acetate (Hex:EA) or *n*-hexane with dichloromethane (Hex: DCM)) and successive extractions, with total volumes that can go from 55 mL up to 750 mL. In terms of recoveries, it presents similar values for most siloxanes, except for lower values for D3 and L3 (in line with the findings of Sanchís et al. (2013) and Bletsou et al. (2013)). Other studies did not even include D3 and L3 in their results, maybe due to the low recoveries. MQLs were also similar. Also, unlike the proposed methodology, the published LLE studies included additional steps that may enable analyte loss, such as: a) extract purification by passing through a 1.0 g anhydrous sodium sulfate cartridge (Xue et al. 2017); b) use of a separatory funnel (sample + extractant) and reduce the volume with rotary evaporator at 25 °C, followed by drying using a sodium sulphate and glass wool column (Sanchís et al. 2013); c) use of a separatory funnel (sample + extractant), and volume reduction with a rotary evaporator at 30-35°C (Bletsou et al. 2013).

Reference	Sample Volume (mL)	LLE extraction solvents	Extraction solvent volume (mL)	Siloxanes studied	Recovery (%)	MQL (ng L^{-1})
Present Work	30	10 mL *n*-Hex	10	L3-L5 D3-D6	13 (D3) - 108 (D5)	0.7 (D5) - 224.9 (D3)
Xu et al. (2017)	100	25 mL *n*-Hex + 20 mL Hex:EA (1:1 v/v)	55	D4-D6	88 (D4) - 94 (D6)	1.7 (D6) - 3 (D4)
Li et al. (2016)	1000	100 mL DCM + 2 x 50 mL DCM	200	L5-L14 D3-D6	87 ± 13 (mean)	0.2 - 2 (not specified)
Sanchís et al. (2013)	500	3 × 250 mL n-Hex	750	L3-L5 D3-D5	40 (D3) - 115 (D5)	0.5 (L5) - 26 (D4)
Bletsou et al. (2013)	100	50 mL *n*-Hex + 25 mL Hex: DCM (1:1 v/v) + 25 mL Hex:EA (1:1 v/v)	100	L3-L14 D3-D7	61 (D3) - 134 (D7)	0.11 (D4) - 12 (L4)

Table 5: Method comparison with literature studies for the analysis of VMSs in wastewater

3.3. Application of the developed method to WWTP samples

Ten wastewater samples (5 influent and 5 effluent) collected in August 2021 (Summer), from a Portuguese WWTP, were analyzed in duplicate. The results (not corrected by the recoveries) are presented in Table 6 and Table 7. It was possible to observe a considerable decrease in the VMSs concentrations, from influent to effluent, possibly due to volatilization in the aeration tanks and partition to sewage sludge. In terms of total VMSs (∑VMSs), the influent average concentration (± standard deviation) was 7.43 ± 1.29 µg L^{-1}, while in the effluent was 0.05 ± 0.01 µg L^{-1}, which is in the same order of magnitude of the concentrations reported in literature. Cyclic VMSs, specially D5 and D6, were the dominant compounds. The highest concentration found in influent was around 7 µg L^{-1} for D5. Effluent samples presented VMSs levels below MDL, with only D5 presenting concentrations up to 0.06 µg L^{-1}. These values are in line with previous studies in literature, in which cyclic VMSs (mainly D5) are usually predominant, concentrations that can reach up to 35.5 µg L^{-1} in WWTP influent (van Egmond et al. 2013) and 6.6 µg L^{-1} in WWTP effluent (Zhang 2014).

Compound	Concentration ± Standard Deviation (µg L^{-1})					
	Influent 1	Influent 2	Influent 3	Influent 4	Influent 5	Influent Mean
L3	nd	nd	nd	nd	nd	nd
L4	nd	nd	nd	nd	nd	nd
L5	0.15	0.12	0.14	0.13	0.09	0.13 ± 0.02
D3	nd	nd	nd	nd	nd	nd
D4	0.33	0.37	0.29	0.32	0.21	0.30 ± 0.06
D5	7.00	6.34	5.73	5.66	4.24	5.79 ± 1.02
D6	1.54	1.13	1.01	1.37	0.94	1.20 ± 0.25
∑VMSs	9.04	7.96	7.17	7.49	5.49	7.43 ± 1.29

Table 6: VMS concentrations found in influent wastewater samples

Compound	Concentration ± Standard Deviation (µg L^{-1})					
	Effuent 1	Effuent 2	Effuent 3	Effuent 4	Effuent 5	Effuent Mean
L3	nd	nd	nd	nd	nd	nd
L4	nd	nd	nd	nd	nd	nd
L5	nd	nd	nd	nd	nd	nd
D3	nd	nd	nd	nd	nd	nd
D4	nd	nd	nd	nd	nd	nd
D5	0.06	0.03	0.04	0.05	0.05	0.05 ± 0.01
D6	nd	nd	nd	nd	nd	nd
∑VMSs	0.06	0.03	0.04	0.05	0.05	0.05 ± 0.01

Table 7: VMS concentrations found in effluent wastewater samples

4. Conclusions

In this study, an alternative methodology to detect and quantify seven VMSs at trace levels in wastewater samples was proposed. This task was accomplished using GC–MS after a small-scale liquid-liquid extraction (LLE). The proposed LLE-GC-MS method emerges as an interesting solution since it proved to be an adequate, simple, low-cost, eco-friendly and fast extraction method for the detection of the VMSs in aqueous samples. It employs low sample (30 mL) and organic solvents (10 mL) volume and is a good alternative to the traditional LLE protocols. It is suitable for the detection of VMSs in streams at higher (*e.g.*, effluents of industries that produce/use siloxanes) or lower (*e.g.*, effluent discharged in the receptor media) concentrations. Consequently, it is a valuable tool to be applied in monitoring, helping understand and assess VMSs risk to the environment and human health. Being usually discharged to a surface water body, treated effluents may be prone to biomagnification in food webs, and possibly cause ecological and toxicological effects.

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