

Response Surface Optimization for Determination of Volatile Organic Compounds in Water Samples by Headspace-Gas Chromatography–Mass Spectrometry Method

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Abstract

The determination of benzene, toluene, p-xylene, tetrachloroethene, chlorobenzene, and dibromomethane in water by headspace analysis combined with gas chromatography–mass spectrometry (HS-GC–MS) has been investigated. An optimization strategy for the analysis of the six volatile organic compounds (VOCs) is presented with the experimental design and response surface methodology aid. Thermostatting time, temperature, and salt quantity were optimized by using a central composite design, and quadratic models relating peak areas to the three factors were built. The mathematical models were tested on a number of simulated data set and had a coefficient of $R^2 > 0.98$. The factor effects were visualized as three-dimensional response surfaces and contour plots. The optimal conditions were achieved in 36.8 min, at 90°C, and with 6 g of NaCl. The method showed a good agreement between the experimental data and predictive values throughout the studied parameter space, and was suitable for optimization studies of the VOCs in water by the HS-GC–MS method.

Introduction

Knowledge obtained regarding the effects related to the presence of volatile organic compounds (VOCs) in the environment today impose a continuous monitoring of their levels of concentrations. Sources of VOCs include production, handling, and use of fuels, solvents, paints, adhesives, deodorants, and refrigerants (1). Many VOCs are also used during agricultural practices, as fumigants (chloroform, 1,3-dichloropropene, dichloropropane, 1,2-dibromoethane, 1,2-dichloroethane, trichloroethane, naphthalene, 1,2-dichlorobenzene), as herbicides (1,4-dichlorobenzene, 1,2,4-trichlorobenzene), and as solvents for pesticides

(xylenes). Trichloroethene is also used as degreaser and tetrachloroethene as industrial solvent. These compounds, the majority of which present some toxic and carcinogenic effects (2), count among the most detected in ground- and surface-water (1). Thus, it is necessary to quantify and identify them in a reliable way. To this end, several techniques are continuously developed for their analysis. Gas chromatography–mass spectrometry (GC–MS) using either static headspace (HS) or dynamic headspace (purge and trap) as sample injection modules are some of the analytical techniques of reference for the analysis of volatile compounds in the environment.

Solid-phase microextraction (SPME) was developed by Pawliszyn and co-workers, and combines sampling and concentration in one step. The method requires no solvent and provides good results for a wide range of analyte concentrations. This technique offers a unique combination of sampling and sample introduction to the chromatographic system by means of a single sample, but may be prone to matrix interferences and also exhibit problems with analyte recoveries (15).

GC–MS using either HS or purge and trap as sample injection modules are the analytical techniques of reference for the analysis of volatile compounds in environmental matrices (3,4). Despite the fact that the detection limits of the HS technique are more than 10 times higher than those of the dynamic technique (5), there are two drawbacks of the last one: first, it requires complex instrumentation; and second, that the smaller size particles (typically 80–100 mesh size) restrict higher flow, limiting sampling speed (6). The best qualities of the HS-GC method are the rather low detection limits with the wide dynamic range and simpler instrumentation compared with the purge and trap technique (5).

This work demonstrates the use of experimental design with the aid of response surface methodology (RSM) to develop a fast separation method (7,8) by combining HS-GC–MS. The influence of the operating conditions on the analysis of six VOCs was exam-

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ined, and good separation conditions were identified with a limited number of experiments. A second-order model correlating the temperature (T), the thermostating time (t), and the ionic strength (Q) with peak areas was conducted by a central composite design (CCD) (9,10). In consequence, models for response were built and optimum conditions for separation were predicted.

The influence of salt addition on the extraction efficiency was investigated because the ionic strength influences the partition coefficient between the gas and the liquid phase. Exact amounts of 0.31, 1.5, 3.25, 5, and 6.19 g of NaCl were added to 20 mL aliquots of ultrapure Milli-Q water (Millipore, Billerica, MA). The maximum quantity was 6.19 g, which corresponded to a maximum concentration of 309.5 g/L salt, because at this level, the saturation level of the solution was reached. Beyond this level, it was impossible to solubilise any more salt crystals.

Experimental

Apparatus

All experiments were carried out by using an HS40 headspace autosampler (PerkinElmer, Waltham, MA) connected to a Turbomass GC-MS (PerkinElmer). The GC column was a 20 m PE-5, 0.18-mm i.d., capillary column coated with 0.18- μ m film thickness, 5% cross-linked phenyl methyl siloxane stationary phase.

Analytical conditions, characteristic ions, and retention times of the different compounds are summarized in Table I.

Chemicals and materials

Toluene and tetrachloroethene were supplied by Prolabo (Paris, France), benzene and chlorobenzene by Merck (Darmstadt, Germany), *p*-xylene was purchased from J.T. Baker (Phillipsburg, NJ), and dibromomethane from Acros (Fair Lawn, NJ). Methanol was used as solvent [Riedel-deHaën (Chrom AR HPLC grade; Seelze, Germany)] and ionic strength was adjusted by sodium chloride addition (Scharlau, Barcelona, Spain).

Procedure

Stock standard solutions of each analyte were prepared in methanol at a concentration of 1.0 mg/mL and stored in glass-stoppered bottles in the dark at 4°C. A standard solution which contained benzene, toluene, *p*-xylene, chlorobenzene, tetrachloroethene, and dibromomethane at individual concentrations of 10 μ g/mL was prepared in methanol by appropriate dilution of the stocks. The standard solution (0.1 mL) was finally injected into HS vials containing 10 mL of ultrapure Milli-Q water and the adequate quantity of NaCl. Vials were then sealed with polytetrafluoroethylene/silicone septa caps and a crimped aluminium closure. Analyses were immediately done to avoid any risk of VOC losses.

Results and Discussion

Experimental design

A central composite design (11) for three factors (temperature,

thermostating time, NaCl quantity) was employed for experimental design. The ranges and the levels of the variables investigated in this study are given in Table II. Each factor in the design was studied at five different levels (-1.68, -1, 0, 1, 1.68). Seven additional experiments were carried out at the central point to estimate the variance of the experimental error.

The selected temperature range was imposed by the equipment. In fact, the minimal value that we were able to reach by the HS apparatus was approximately 38°C. Additionally, it is generally recommended in HS analysis not to use high temperature in order to avoid the over-pressurization of the vial sample, and so avoid accidents. Thus, a value of approximately 90°C was selected as the maximum temperature.

To ensure the maximum derivatization and vapor equilibrium of the VOCs, the thermostating time was varied from approximately 3 to 37 min (12,13,14). For most compounds, the extraction efficiency increased with the extraction time and temperature, until equilibrium was reached after an average of 30 min at 90°C.

Table I. Operational Conditions and Chromatographic Characteristics of the Target Compounds

Gas chromatograph	
Carrier	Helium, 3 mL/min for 0.25 min, then 8 mL/min down to 1 mL/min and hold
Splitflow	10 mL/min
Oven temperature	50°C for 3 min, 10°C/min to 180°C, hold for 2 min
Injector temperature	150°C
Headspace autosampler	
Pressurization time	3.0 min
Inject time	0.06 min
Transfer-line temperature	120°C
Needle temperature	110°C
Mass spectrometer	
Transfer-line temperature	200°C
Ion-source temperature	180°C
Mode	El, full scan with selected ion recording
<i>m/z</i> Full scan	<i>m/z</i> 45 to 200
Dwell time	0.02 s
Spectrometric acquisition conditions of the target compounds	
Benzene	$t_R = 1.24 \pm 0.04$ (s)* <i>m/z</i> (SIR) = 77-78 [†]
Dibromomethane	$t_R = 1.52 \pm 0.04$ (s) <i>m/z</i> (SIR) = 93-174
Toluene	$t_R = 2.16 \pm 0.05$ (s) <i>m/z</i> (SIR) = 91-92
Tetrachloroethene	$t_R = 2.74 \pm 0.09$ (s) <i>m/z</i> (SIR) = 166-168
Chlorobenzene	$t_R = 3.56 \pm 0.08$ (s) <i>m/z</i> (SIR) = 77-112
<i>p</i> -Xylene	$t_R = 4.07 \pm 0.05$ (s) <i>m/z</i> (SIR) = 91-106
* t_R : retention time.	
† SIR: selected ion recording.	

The influence of salt addition on the extraction efficiency was investigated because the ionic strength influences the partition coefficient between the gas and the liquid phase. Exact amounts of 0.31, 1.5, 3.25, 5, and 6.19 g of NaCl were added to 20 mL aliquots of ultrapure Milli-Q water. The maximum quantity was 6.19 g, which corresponded to a maximum concentration of 309.5 g/L of salt, because at this level, the saturation level of the solution was reached. Beyond this level, it was impossible to solubilize any more salt crystals. The experimental design matrix in coded units is given in Table III.

Model fitting and statistical analysis

The responses and corresponding factors are modeled and optimized using the RSM. In our case, the results are fitted with a second order polynomial equation:

$$Y = a_0 + a_1Q + a_2T + a_3t + a_{11}Q^2 + a_{22}T^2 + a_{33}t^2 + a_{12}QT + a_{13}Qt + a_{23}Tt$$

In this equation, Y is the predicted response, a_0 is the intercept coefficient, a_1 , a_2 , and a_3 are the linear terms; a_{11} , a_{22} , and a_{33} are the squared terms, a_{12} , a_{13} , and a_{23} are the interaction terms; and X_1 , X_2 , and X_3 represent the uncoded for the independent variables.

The significance of each coefficient was determined using the F-test and p-value. The corresponding variables would be more significant if the absolute F value becomes greater and the p-value becomes smaller (7).

The results obtained clearly showed the largely significant effects of the temperature 'T', as well as the salt quantity 'Q' and the thermostating time 't'. In the case of benzene, the highest t-value was obtained with the factor temperature ($t_{\text{student}} = 1497.866$). The importance of this parameter is also evident given its second order effects ($T^2 \rightarrow 1323.843$; $QT \rightarrow 2076.754$; $Tt \rightarrow 1260.453$), which is also the case of tetrachloroethene, chlorobenzene, and *p*-xylene. For the other compounds, it is rather the salt amount which has the main effect, with a more significant contribution of the thermostating time for the toluene. Finally, all the t-values which we have obtained are largely higher than $t_{0.975, 6} = 2.447$; this implies that the three selected factors contribute simultaneously and in a significant way on the variance of the different responses, which is also confirmed by the P-values ($P = 0.000$ for the whole of the cases).

The fit quality of the models was judged from their coefficients of determination. The adequacy of each model was checked with the analysis of variance (ANOVA) using Fisher F-test (7–15). The results obtained are summarized in Table IV.

The best result was obtained in the case of benzene, for which the regression coefficient was estimated with a good determination coefficient of $R^2 = 0.9964$. The R^2 value means a good agreement between the experimental and predicted

values of the fitted model. It implies that 99.64% of the total variation in the response is justified by the model.

In general, the calculated F-value should be several times greater than the tabulated one for the model to be considered good. In our case, the calculated F-value corresponding to the six VOCs is remarkably higher than that of F distribution table ($F_{0.05, 9, 6} = 4.105$) at 5% level of significance implying that the variation accounted for by the model is significantly greater than the unexplained variation.

Determination of optimal extraction conditions

The quadratic response surface for the three factors involved generates a four-dimensional response surface, which can be illustrated in a three-dimensional (3D) response surface. The response models were mapped against two experimental factors while the third was held constant at its optimum. That way, 3D responses are depicted in Figure 1 (See page 8A).

Table II. Experimental Range and Levels of the Independent Test Variables

Variables	Range and levels				
	-1.68	-1	0	+1	+1.68
Temperature (°C)	39.8	50	65	80	90.2
Thermostating time (min)	3.2	10	20	30	36.8
NaCl amount (g)	0.31	1.5	3.25	5	6.19

Table III. The Central Composite Design Matrix of Three Test Variables in Coded Units Along With the Observed Responses*

No.	Q	T	t	Peak area					
				Y ₁	Y ₂	Y ₃	Y ₄	Y ₅	Y ₆
1	-1	-1	-1	20182	5203	6231	689	605	574
2	+1	-1	-1	25009	9370	11378	787	686	962
3	-1	+1	-1	46433	28120	31484	10407	11189	7765
4	+1	+1	-1	187486	69955	111253	65002	55072	41870
5	-1	-1	+1	33033	24327	26367	6870	1583	1054
6	+1	-1	+1	35120	27369	30195	8580	3861	2162
7	-1	+1	+1	140139	66694	78285	29524	38058	30782
8	+1	+1	+1	288537	117303	145400	102777	96313	80636
9	-1.68	0	0	21808	6497	6581	732	669	623
10	+1.68	0	0	117134	61779	77650	28938	36347	22627
11	0	-1.68	0	19670	4820	5344	648	538	483
12	0	+1.68	0	257120	98484	122189	90870	79504	60970
13	0	0	-1.68	21325	6327	6387	720	653	616
14	0	0	+1.68	102838	58931	67008	27730	26930	20983
15	0	0	0	69434	42956	58915	13910	15497	10474
16	0	0	0	69415	42964	58955	13924	15493	10421
17	0	0	0	69513	42925	59037	13947	15420	10570
18	0	0	0	69420	42871	59042	13980	15477	10566
19	0	0	0	69409	43011	58963	13889	15573	10505
20	0	0	0	69468	42813	58920	13901	15512	10568
21	0	0	0	69436	42920	58971	13916	15460	10441
22	0	0	0	69526	43037	59010	13931	15546	10455

*1: benzene; 2: dibromomethane; 3: toluene; 4: tetrachloroethene; 5: chlorobenzene; 6: *p*-xylene.

Figure 1A shows the response surface function developed by the model for temperature and salt quantity; the response showed that the more temperature and salt quantity, the more pronounced the response in the maximum direction. Figure 1B shows the response surface function developed by the model for thermostating time and salt amount; the response presented a maximum at 36.8 min and 6 g, respectively. Figure 1C shows the function for temperature and time, giving a maximum for temperature of 90°C and for thermostating time of 36.8 min. Resulting from this study, the optimal conditions for the analysis of the six VOCs were selected as temperature, 90°C; thermostating time, 36.8 min; and salt quantity, 6 g. Figure 2 shows the chromatogram total ion chromatogram mode of the ppm level standard VOCs mixture spiked into the water sample. Mass spectra and library search also confirmed the identity of these 6 compounds. The calculations from the optimization toolbox (MAPLE 9.5) supported the conclusion. The results showed that the optimal extraction conditions were the same for the various test compounds; maximum values for responses obtained were between 152442.10 (*p*-xylene) and 521483.18 (benzene).

The agreements between observed and predicted responses for each compound under optimal conditions are given in Table V. The results showed a good accordance between the predictive and the experimental data with a correlation coefficient of 0.9998 and 1672.22 as standard error. The mathematical models developed for peak areas proved to be effective and accurate for test compounds. The chromatogram obtained under optimal conditions is shown in Figure 2. Mass spectra and library search

also confirmed the identity of these 6 compounds.

The effect of temperature on the extraction efficiency was studied under the optimal conditions ($t = 36.8$ min and $Q = 6$ g) with a temperature range from 50°C to 90°C. The peak area, which corresponds to the vapor phase distribution, increases with the rise of thermostating temperature. Responses obtained showed a good enhancement of sensitivity for all the compounds. The best result was achieved with *p*-xylene, of which the peak area, at 90°C, was approximately 22 times as that at 50°C.

Essentially, the time needed for headspace equilibration depends on the diffusion of the volatile sample components into and from the sample matrix. In this case, the equilibration time depends on both the thermostating temperature and the quantity of NaCl added to the sample. A study of the effect of the thermostating time on the results obtained by combining HS-GC-MS was also performed, under the optimal conditions ($T = 90^\circ\text{C}$ and $Q = 6$ g). Different responses were found for the compounds, depending on their volatility and distribution constants. All the peak area obtained became constant after approximately 29–35 min for the six VOCs. With lower temperature and salt quantity, more time was needed to reach the equilibrium.

The effect of decreasing solubility of organic compounds with the addition of salt is known as the “salting out” effect (16). By adding a salt to the aqueous samples, the ionic strength of water can be increased; this makes organic compounds less soluble, increasing the partition coefficients and, consequently, the GC-MS response. In our case, a notable increase in sensitivity was achieved for all the target compounds. Responses obtained

Table IV. Predicting Models and ANOVA Results for the Six VOCs*

Compounds	Predicting models	F	P	$R_a^{2\dagger}$	R^2	% Variances described by the model
Benzene	$Y_1 = 614159.72 - 72272.61 Q - 17605.94 T - 183.027 6384.31 t + 504.78 Q^2 + 115.41 T^2 - 10.72 t^2 + 1345.41 QT + 32.89 Qt + 143.16 Tt$		< 0.05	0.9909	0.9964	99.64
Dibromomethane	$Y_2 = 71165.23 - 15221.60 Q - 2753.78 T - 94.473 267.77 t - 644.70 Q^2 + 18.80 T^2 - 25.09 t^2 + 405.88 QT + 54.64 Qt + 40.67 Tt$		< 0.05	0.9825	0.9930	99.30
Toluene	$Y_3 = 48265.45 - 21232.20 Q - 2720.60 T + 71.294 1937.20 t - 1220.06 Q^2 + 17.49 T^2 - 56.56 t^2 + 656.71 QT - 99.81 Qt + 35.00 Tt$		< 0.05	0.9768	0.9907	99.07
Tetrachloroethene	$Y_4 = 276929.94 - 36581.17 Q - 7891.94 T - 35.987 2250.30 t + 321.14 Q^2 + 53.07 T^2 + 7.67 t^2 + 600.19 QT + 144.79 Qt + 35.76 Tt$		< 0.05	0.9545	0.9818	98.18
Chlorobenzene	$Y_5 = 222814.17 - 29352.85 Q - 6232.05 T - 179.235 2890.58 t + 459.73 Q^2 + 40.13 T^2 - 2.63 t^2 + 475.14 QT + 118.35 Qt + 53.30 Tt$		< 0.05	0.9907	0.9963	99.63
<i>p</i> -Xylene	$Y_6 = 207350.59 - 25068.37 Q - 5559.16 T - 45.988 3241.93 t + 356.66 Q^2 + 34.93 T^2 - 8.00 t^2 + 392.68 QT + 117.64 Qt + 50.09 Tt$		< 0.05	0.9643	0.9857	98.57

* 1: benzene; 2: dibromomethane; 3: toluene; 4: tetrachloroethene; 5: chlorobenzene; 6: *p*-xylene.
 $\dagger R_a^{2\dagger}$: determination coefficient adjusted to the model.

after the addition of 6 g of NaCl were between 2 and 3 times higher than the ones obtained with 1 g of salt, depending of the compound. The peak areas obtained increased with an increase in both thermostating temperature and time.

HS-GC–MS linearity, precision, sensitivity, limit of detection, and limit of quantitation

Calibration studies were performed to evaluate the linearity of the HS-GC–MS method; the concentration range was from 10 to 200 µg/L. The correlation coefficients (R^2), shown in Table VI, demonstrated a directly proportional relationship between the extracted amount of the VOC and its initial concentration in the sample.

Detection and quantitation limits were calculated on the basis of the standard deviation of residuals ($S_{y/x}$) (17). The limits of quantitation, expressed as ten times the $S_{y/x}$ divided by the slope of calibration graphs, were between 0.25 µg/L (benzene) and 0.83 µg/L (*p*-xylene). Results obtained are shown in Table V.

Sensitivity [peak area/(µg/L)] expresses the variation of the response as a function of the sample's concentration; values obtained were between 1828.43 (dibromomethane) and 5207.59 (benzene). These values depend on the mass spectrometer, the multiplier's voltage, and the chromatographic conditions, as well as the column used, etc.

The precision of the experimental procedure was also evaluated; a series of 10 consecutive analyses of a water sample with 50 µg/L of each VOC gave a relative standard deviation ranging from 0.85% to 3.51%.

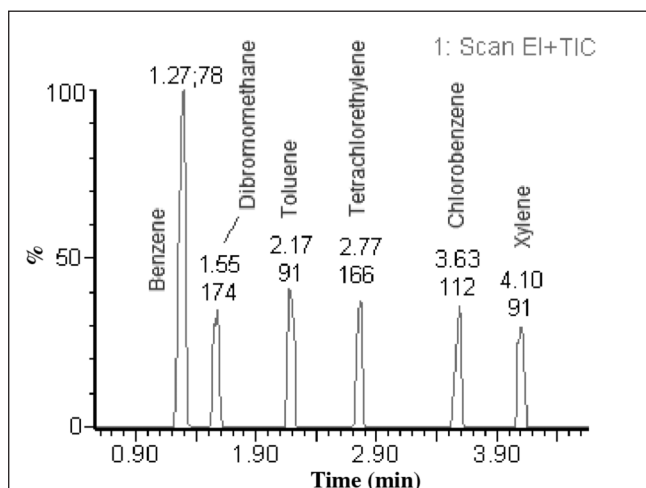


Figure 2. Chromatogram obtained under the optimal conditions; $C_i = 0.1$ µg/mL, $T = 90^\circ\text{C}$, $t = 36.8$ min, and $Q = 6$ g.

Table V. The Comparison of Predictive and Observed Responses of Analytes Under Optimal Conditions: 90°C , 36.8 min, 6 g

	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6
Y_{obs}	522589	183975	219225	194292	181863	153353
Y_{pred}	521483	183359	221060	197091	182338	152442
$ Y_{\text{obs}} - Y_{\text{pred}} /Y_{\text{obs}}$	0.0021	0.0033	0.0084	0.0144	0.0026	0.0059

Finally, the proposed method was applied to the determination of VOCs in an industrial wastewater from Tunis, Tunisia. Three of the compounds included in this study were found in the sample. The chromatogram, obtained under the optimal conditions already determined, is presented in Figure 3. The mean concentrations ($n = 3$) of benzene, toluene, and *p*-xylene were 0.6 ± 0.1 µg/L, 2.6 ± 0.2 µg/L, and 1.8 ± 0.1 µg/L, respectively.

Conclusions

It can be concluded that the method was applied successfully for the analysis of VOCs investigated in this study.

The optimization of process parameters was studied using RSM. The mathematical models developed for relating peak surface to thermostating time, temperature, and ionic strength proved to be an efficient strategy for optimization of the HS-GC–MS method. It provides accurate prediction of response for test compounds, with acceptable errors. A significant good fit with the models was found between predicted and observed data. The use of RSM for the optimization has several advantages: (i) the response values at certain ranges of process parameters can be precisely predicted by the models; (ii) the optimal value of each response can be obtained at the corresponding optimal process parameters; and (iii) the operating conditions suitable for the analytical method can be recommended.

Hence, the RSM together with the fast separation properties of the HS-GC–MS process could be applied in future optimizations of VOCs in other matrices separations, in particular because it is a simple, solvent-free, inexpensive, and efficient analytical method.

Table VI. Analytical Performance Characteristics of HS-GC–MS for VOC Determination in Water

Compounds	Correlation coefficients (R^2)	LOD (µg/L)	LOQ (µg/L)	Sensitivity [peak area/(µg/L)]	Precision (RSD %)
Benzene	0.9985	0.08	0.25	5207.59	1.15
Dibromomethane	0.9988	0.23	0.70	1828.43	0.85
Toluene	0.9976	0.19	0.59	2219.19	1.36
Tetrachloroethene	0.9969	0.21	0.66	1946.78	2.32
Chlorobenzene	0.9981	0.23	0.71	1882.36	2.96
<i>p</i> -Xylene	0.9986	0.27	0.83	1510.12	3.51

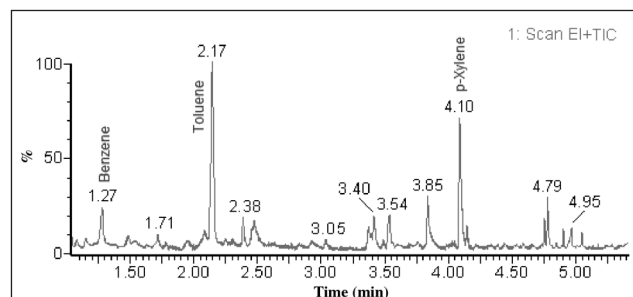


Figure 3. Chromatogram of an industrial wastewater sample; $T = 90^\circ\text{C}$, $t = 40$ min, and $Q = 6$ g.

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