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Optimization of supercritical fluid extraction of phenol and cresols in soil samples☆

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Abstract

Two- and three-level factorial designs have been used to optimize the supercritical fluid extraction of underivatized phenol and cresols (*o*-, *m*- and *p*-cresol) in soil samples with a high content of carbon. An overall eight variables [carbon dioxide flow-rate, fluid density, extraction cell temperature, static extraction time, nozzle and trap temperatures, amount of methanol (as modifier) and the time of contact between the added modifier and sample prior to extraction] were considered. The results suggest that thimble temperature and fluid density are statistically significant factors to the overall extraction yield of the four analytes considered. Also, the static extraction time appears to be significant in the cases of *m*- and *o*-cresol. Special attention was paid to developing suitable test materials for this type of optimization process. Moreover, validation of the extraction process was carried out by processing a certified reference material.

1. Introduction

The interest in supercritical fluid extraction (SFE) as a sample processing technique for the extraction of organic pollutants from environmental matrices has grown rapidly in recent years. The SFE technique minimizes sample handling, provides fairly clean extracts, expedites sample preparation and reduces the use and disposal of environmentally aggressive solvents [1,2]. Additionally, in many cases, SFE provides recoveries as good as or even better than those of more conventional solvent extraction techniques [3–6].

Supercritical CO_2 is by far the most commonly used fluid in SFE. However, quantitative extraction of polar analytes such as phenol and its derivatives requires the addition of an organic modifier, methanol being the most usual choice [7–9].

When developing a SFE method, trial-and-error procedure is known to be not very effective for finding out the true optimum since many variables have to be considered simultaneously. Thus, formal optimization methods are generally preferred. Factorial designs have been used for the simultaneous determination of various analytical SFE parameters including temperature, pressure, CO_2 density, extraction time, fluid flow-rate [10–15]. However, only two or three

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variables are considered in most cases, so a reasonably large number of experiments must be performed in order to detect potential interaction effects between the experimental variables. These effects cannot be detected by the classical trial-and-error (univariate) method. The use of screening designs such as Plackett–Burman designs [16] allows selection, from the numerous variables available, of the most meaningful effects from a reduced number of experiments. Thus, the full set of variables with the potential to affect the determinations can be considered within practical time and cost margins.

On the other hand, a number of reported methods for soil SFEs have been optimized using samples which were freshly spiked with known amounts of analytes immediately prior to extraction [17,18]; the interactions between the sample matrix and the analytes, which may give rise to spurious results when the optimized procedure concerned is applied to real samples, are virtually suppressed [19]. On account of the restricted availability of certified reference materials for contaminated soils, one should bear in mind the need not to suppress analyte–matrix interactions in preparing experimental samples for optimization study purposes.

This paper reports the results obtained in the development and optimization of a method for the supercritical fluid extraction of phenol and the three isomers of cresol in soil samples with high carbon content which usually makes phenol extraction a difficult task. Various factorial designs have been tested to optimize eight experimental variables, namely CO_2 density and flow-rate, extraction cell temperature, static extraction time, nozzle and trap temperatures, amount of methanol added as modifier and contact time prior to extraction. Optimization was targeted at the maximum extraction yield of each individual analyte and a final compromise was obtained for the overall extraction yield of all the species considered. The procedure was developed by using a spiked soil sample prepared in such a way that potential interactions between the analytes and the matrix were not suppressed. Finally, recoveries were assessed by using a commercially available certified reference material.

2. Experimental

2.1. Apparatus and reagents

Phenol and cresol standards were supplied by Aldrich Chemie (Steinheim, Germany). Methanol and *n*-hexane were purchased from Romil Chemicals (Cambridge, UK). Standard stock solutions were prepared by weighing an appropriate amount of each and diluting to 10 ml with *n*-hexane. Working solutions were made by appropriate dilution of the stock solution. All solutions were stored at 5°C in the dark. For quantitative GC determinations, calibration was carried out at four concentration levels for each species spanning the range 0.5–10 μg/ml.

Extractions were carried out with 99.995% pure carbon dioxide from Carburos Metálicos (Barcelona, Spain). The pump and collection trap were cooled with industrially pure CO_2.

Optimization experiments were performed on an industrial lignite mining soil obtained from the slag of the Power Station of "Puentes de García Rodríguez" (La Coruña, Spain), which had a 7.2% carbon content. Several kilograms of this soil were dried in an oven at 40°C, ground and sieved to a particle size below 60 μm. The sample (200 g) was spiked by slowly pouring it over 250 ml of methanol containing phenol, *o*-cresol, *m*-cresol and *p*-cresol. The dough formed was mechanically mixed for several minutes. The sample was then allowed to air-dry for 4 days and stored in the dark for 40 days before analysis. On the assumption that no phenol or cresol loss occurred during drying or storage, the expected final concentration was calculated to be 3.6, 4.3, 4.2 and 3.9 μg/g for phenol, *o*-cresol, *m*-cresol and *p*-cresol, respectively, on a dry-weight basis. It was also assumed that the contaminants were uniformly distributed in the sample and that, because the sample contained residual moisture during the storage period, any analyte–matrix interactions would have occurred to an extent similar to that in real contaminated soil of identical properties.

Phenol and cresol recoveries were determined by using a certified reference material supplied by Environmental Resource Associates (Arvada, CO, USA), viz. ERA soil (Lot. no. 329). The certified contents for phenol, *o*-cresol and *m*-cresol were 9.88, 6.26 and 5.98 μg/g, respectively. This material, which was ground and sieved in the laboratory to an average particle size of 60 μm because the particle distribution of the original material appeared very heterogeneous, had no addition of *p*-cresol.

SFE experiments were performed on a Hewlett-Packard 7680A supercritical fluid extractor using standard steel cells of 7.0 ml inner volume. The system was altered as described below. The collection trap (7 cm long × 5 mm I.D., 540 μl inner volume) was packed with Hypersil ODS of 30 μm average particle size.

Extracts were analysed on a Hewlett-Packard 5890 gas chromatograph equipped with a flame ionization detector (FID) and a Hewlett-Packard 7673A autosampler. A 60 m × 0.56 mm I.D., 0.2 μm phase thickness, fused-silica chromatographic column coated with di-isodecyl-phthalate (DIIDP) (Resstek, Bellefonte, PA, USA) was used, which allows good resolution of the three cresols. Chromatographic data were acquired and processed with a Hewlett-Packard 3365A data station. Table 1 summarizes the chromatographic conditions used.

Table 1
GC operating conditions

Parameter	Operating conditions
Injection port temperature	125°C
Injection mode	splitless
Injection volume	2 μl
Splitless time	60 s
Column	60 m × 0.56 mm,
DIIDP	0.2 μm film thickness,
Carrier gas	Nitrogen (99.9995%)
Carrier gas flow-rate	5.8 ml/min
Carrier gas pressure at column head	50 kPa
Oven temperature	100°C
FID temperature	150°C

2.2. Sample preparation

Irrespective of the working conditions imposed by the particular factorial design, all the samples were prepared by following the same procedure prior to extraction. In order to minimize contamination and plugging of the sintered disks, the top and bottom caps of the extraction thimble were fitted with two filter paper disks of the same diameter as the cap I.D. A piece of Teflon tubing of the same outer diameter as the thimble I.D. was also placed in the thimble to avoid potential interactions between the steel walls and the analytes. The lower half of the tube was packed with Celite and the sample (to which the amount of methanol dictated by the particular experiment was added) and the upper half with more Celite to the top. The tube was sealed with the top cap and placed in the extraction chamber. The static and dynamic supercritical fluid CO_2 extraction program was then started under the conditions appropriate to the particular factorial design tested. Finally, the extracted and trapped analytes were eluted from the trap with 2 × 1 ml of *n*-hexane and collected in two 2-ml vials. After checking the volume in the vials, the extracts were separated by direct GC under the conditions shown in Table 1.

In all the experiments the dynamic extraction stage was split into successive segments eluting the trapped material after 5, 10, 15 and 30 min. Total recovery in each experiment was calculated by adding the amount of the analytes found in each collected fraction. The analytes were never detected in the fraction which was collected after 30 min elution. Thus 30 min was considered sufficient to complete the extraction, even in cases with slow extraction kinetics.

3. Results and discussion

3.1. Validation of the analytical procedure for phenol and cresols by GC

Chromatographic conditions were optimized with respect to the resolution of the four analytes considered. These conditions are summarized in

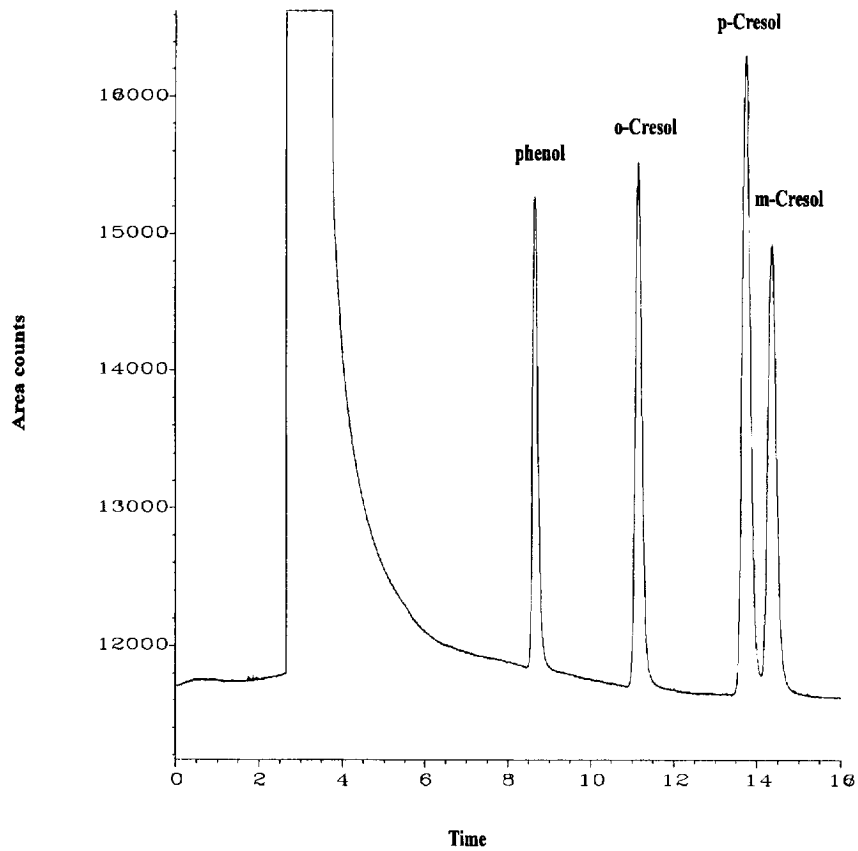

Fig. 1. Chromatogram for a working solution containing phenol and three isomers of cresol.

Table 1. By using a DIIDP chromatographic column one can obtain adequate resolution of all the species as can be seen in the chromatogram in Fig. 1. Other stationary phases do not provide resolution between *m*-cresol and *p*-cresol.

As noted under the Experimental section, calibration graphs were obtained at five concentration levels using appropriately diluted standards. Each concentration level was injected in triplicate. The chromatographic peak areas were fitted by linear regression; the results are given in Table 2. The repeatability of the chromatographic procedure was assessed by performing six consecutive injections of a standard solution containing the four analytes. The results (between-injection repeatability data) are also

Table 2
Calibration and statistical validation parameters

Parameter	Phenol	*o*-Cresol	*m*-Cresol	*p*-Cresol
Calibration range (μg/ml)	0.54–10.70	0.48–9.60	0.53–10.52	0.58–11.56
Correlation coefficient	0.9999	0.9999	0.9999	0.9999
Detection limit (ng/ml)	12.5	11.0	10.5	13.0
Quantification limit (ng/ml)	41.7	36.7	35.0	43.3
Between-injections R.S.D. (%)	1.5	2.2	1.2	0.9

Table 3
SFE parameters employed in the homogeneity study

Parameter	Units
Carbon dioxide density	0.65 g/cm^3
Carbon dioxide flow-rate	1.2 ml/min
Extraction cell (thimble) temperature	80°C
Static extraction time	5 min
Nozzle (restrictor) temperature	45°C
Trap temperature	20°C
Dynamic extraction time	30 min
Amount of methanol	10 μl
Contact time before extraction	0 min

given in Table 2 along with detection and quantitation limits for direct injections of standards at a signal-to-noise ratio of three and ten, respectively.

3.2. Evaluation of the homogeneity of the laboratory-spiked soil sample

The homogeneity of the analyte distribution in the spiked soil sample was evaluated after 40 days of storage. Tentative extraction conditions were established empirically from experiments performed to determine the potential original extent of phenol and cresols contamination. These tests revealed the absence of signals for these compounds in the original soil; on the other hand, analyte additions carried out immediately prior to analysis led to the working conditions summarized in Table 3. Such conditions were systematically tested on sample masses from 0.1 to 1.0 g. The graphs in Fig. 2 show poor recovery for sample sizes below 0.25 g; however, variance appears to be rather con-

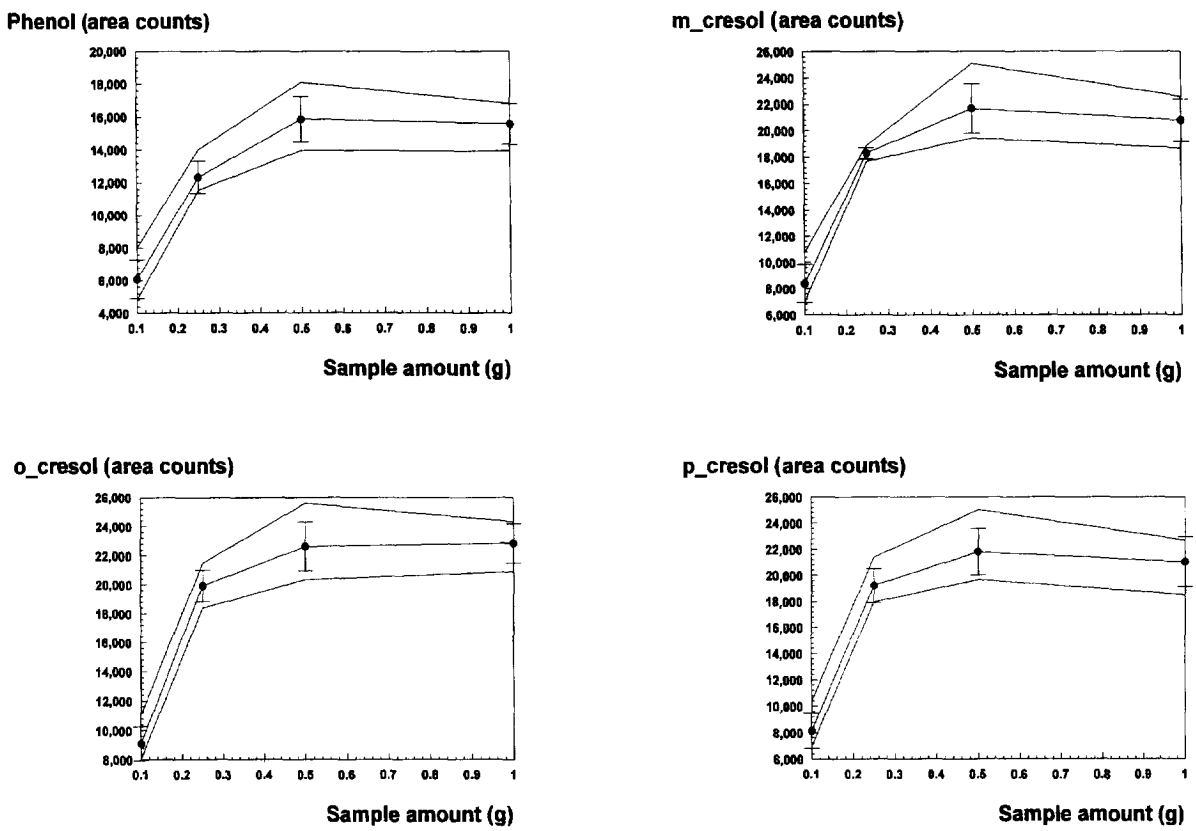

Fig. 2. Evaluation of the homogeneity of the material used to optimize the extraction procedure through the variation of the mean values and standard deviations obtained with the amount of sample subjected to extraction and analysis.

stant irrespective of the sample mass considered. Above a sample of size 0.5 g, the material was quite homogeneous with regard to the four analytes.

We chose 1.0 g as the optimum sample size for subsequent experiments in order to prevent variability between sample portions from masking the influence of the experimental variables.

3.3. Optimization of the SFE process. Factorial designs

In principle, SFE overall recovery of phenol and the cresols from soil samples could be influenced by a number of experimental variables, namely: CO_2 flow-rate (1) and density (2), temperature of the extraction thimble (3), static extraction time (4), temperatures of the nozzle (5) and trap (6), amount of SF modifier (methanol in this case) (7), and contact time between this modifier and the sample prior to extraction (8). A full two-level factor design would involve an overall of $2^8 = 256$ experiments, in addition to the replicates needed for statistical evaluation of the coefficients for the fitted model and the degree of coincidence of the hyperplane obtained. We therefore chose a folded Plackett–Burman $2^8 \times 3/64$, type III resolution design allowing three degrees of freedom, which involved ten randomized runs plus two centered points [20]. This design possesses an alias structure such that main effects are clear of two-factor interactions but these are partially confounded with other two-factor interaction effects. Table 4 lists the upper and lower values given to each factor. Such values were selected from available data and experience gathered in the experiments for the evaluation of sample homogeneity described above. Table 5 shows the design matrix for this experiment and the extraction yield for each analyte.

An analysis of the results given in Table 5 produced the main effect Pareto chart shown in Fig. 3 which is the result of mixing the individual Pareto charts for each species. This process of mixing Pareto charts violates the condition of sorting the effects but allow a direct comparison of the results for the four compounds considered. The conclusions are that CO_2 density (higher densities render the supercritical fluid more polar and thus more able to extract polar compounds like the ones considered) and the extraction cell temperature (both major variables in SFE processes) were statistically significant for all analytes considered except (thimble temperature) in the case of *o*-cresol. Moreover, static extraction time also appears significant for *p*-cresol. In all cases these factors positively influenced the extraction efficiency. Surprisingly, the amount of modifier (above a minimum) or the contact time between the added modifier and the sample do not appear to be influential.

Because a design of this type does not allow the direct evaluation of interaction terms for two

Table 4
Factor levels in the first (folded Plackett–Buman) factorial design

Factor		Units	Levels	
Variable	Key		Low (−)	High (+)
Thimble temperature	A	°C	50	98
Static extraction time	B	min	0	10
Nozzle temperature	C	°C	45	60
Trap temperature	D	°C	10	40
CO_2 density	E	g/cm^3	0.5	0.75
CO_2 flow	F	ml/min	0.8	1.5
Amount of methanol	G	μl	50	200
Contact time before extraction	H	min	0	30

Table 5
Design matrix and response values in the first (folded Plackett–Burman) factorial design

Run	A	B	C	D	E	F	G	H	Recovery (%)			
									Phenol	*o*-Cresol	*m*-Cresol	*p*-Cresol
1	−	−	−	−	−	−	−	−	28.5	53.6	35.7	35.9
2	−	+	+	−	+	−	−	−	63.4	82.2	73.6	73.1
3	+	−	−	−	+	+	+	−	66.0	66.0	70.4	76.2
4	+	+	+	−	+	+	−	+	72.5	75.8	80.5	80.2
5	−	−	−	+	+	+	−	+	46.8	62.5	57.4	56.5
6	+	+	−	+	−	−	−	+	48.4	64.1	54.2	58.3
7	+	−	+	−	−	−	+	+	63.7	55.0	61.4	50.0
8	+	−	+	+	−	+	−	−	48.1	63.7	55.9	54.6
9	−	−	+	+	+	−	+	+	45.1	64.8	60.3	58.8
10	+	+	−	+	+	−	+	−	69.7	73.9	75.8	74.1
11	−	+	+	+	−	+	+	−	25.8	54.1	48.3	52.4
12	−	+	−	−	−	+	+	+	46.5	60.7	55.2	53.7

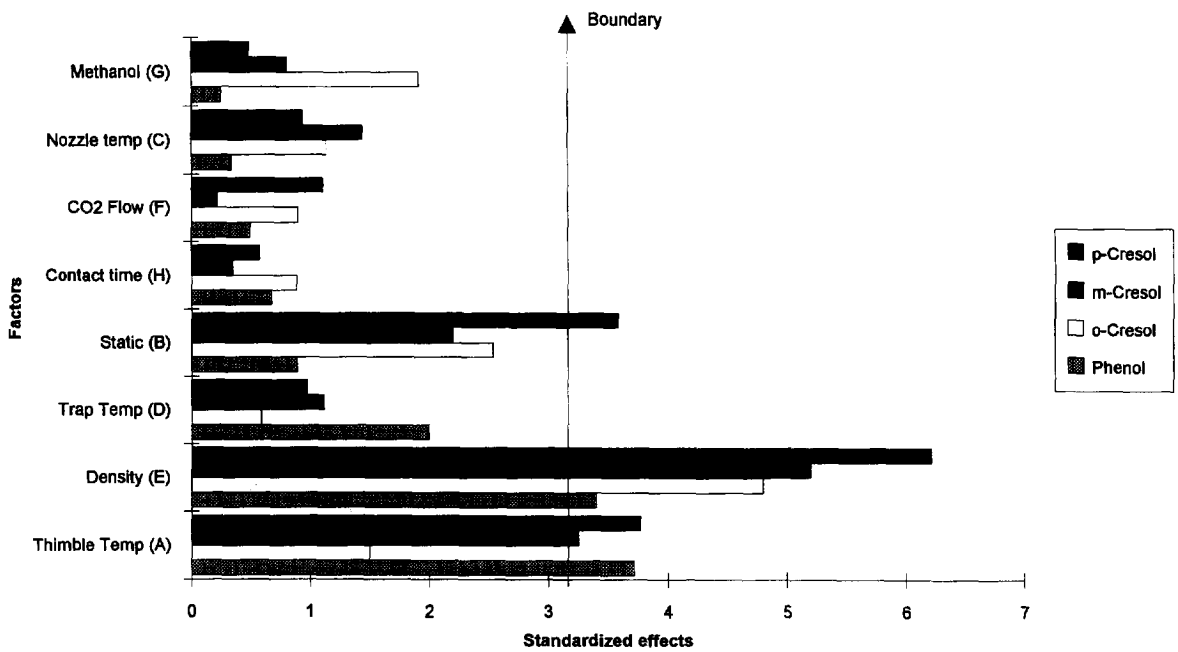

Fig. 3. Pareto chart for the standardized main effects in the first factor design (folded Plackett–Burman model). The vertical line indicates the statistical significance bound for the effects.

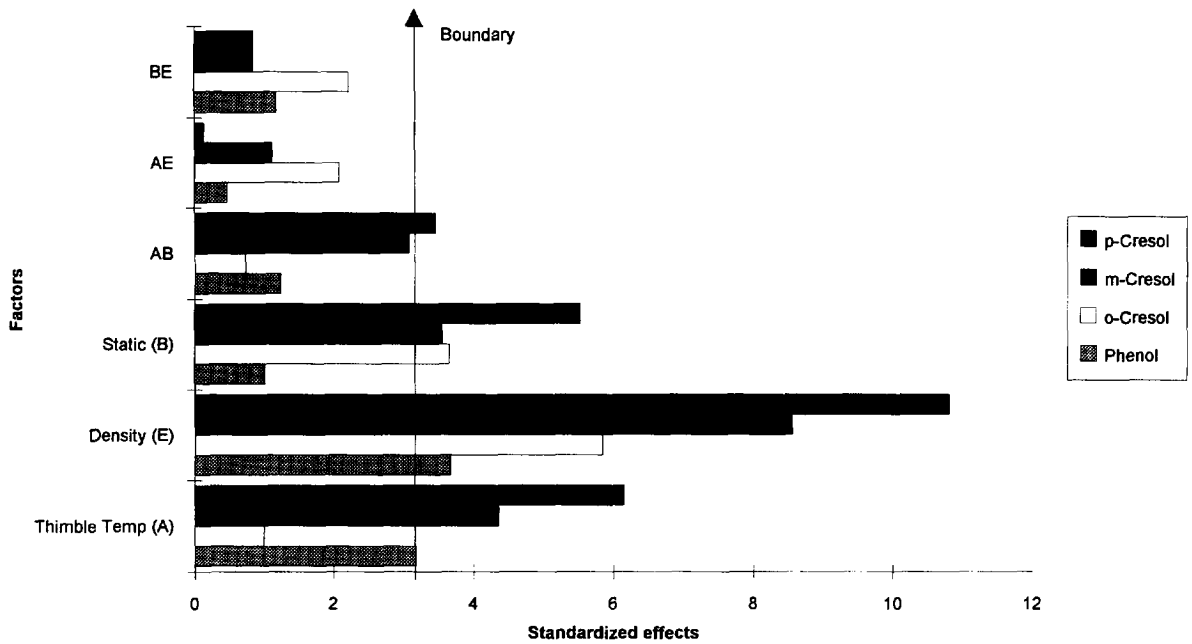

Fig. 4. Pareto chart for main effects (after discarding effects C, D, F, G and H) and interaction effects between variable pairs. The vertical line indicates the statistical significance bound for the effects.

or more factors, we discarded some of the factors initially considered because of the results obtained with the use of a more restrictive model which includes only the factors appearing as statistically significant and two-factor interactions between these selected factors. The Pareto charts in Fig. 4 summarize the results obtained. As expected, CO_2 density appears as the most significant factor. Thimble temperature and static extraction time also have an influence for most of the analytes, and the interaction of factor A (thimble temperature) and factor B (static extraction time) appears to influence the *p*-cresol extraction yield. This correlation is rather logical. When the static extraction time is decreased, a higher thimble temperature is needed to force compound extraction. In contrast, extended static extraction times allow lower thimble temperatures to be used in order to obtain equivalent extraction efficiencies.

However, the conditions under which the experiment was conducted appeared not to be optimal. Response surfaces (Fig. 5) tend to maximum allowable values for static extractions, density and thimble temperature. However, the SFE instrument used in these experiments cannot be set to levels higher than those considered as high in this design, given that a pressure limit of ca. 380 bars was obtained for maximum values of density and thimble temperature. Because the results suggested that density was the most significant factor, we decided to outline a new factorial design in the highest possible densities' region, consequently decreasing thimble temperatures. In this second design only the three significant factors were considered. A central 2^3+ star, orthogonal composite design involving 16 runs using low, medium and high levels depicted in Table 6 was conducted. Table 7 summarizes the results obtained, together with the corresponding design matrix. As can be seen from the Pareto chart in Fig. 6, only thimble temperature appears as statistically significant for all analytes considered. The displacement of this new design has moved us far away from the optimum, and the results once more suggest the need to force density and thimble temperature to their maximum allowable values (see Fig. 7

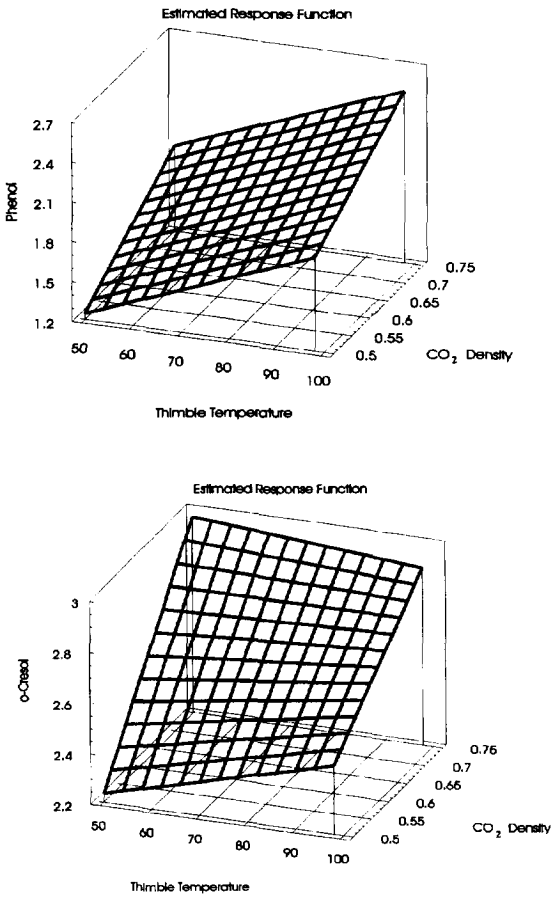

Fig. 5. Response surface estimated from the first factor design, obtained by plotting the two statistically significant main factors.

where only one of the analytes has been selected to show the influence of the variables; analogous results were obtained for the other analytes). The curvature of the response surfaces with the static extraction time is striking. Since no interaction effects are noticeable in Fig. 6, this curvature has to be attributed to the quadratic term BB which appears in the Pareto analysis as a negative term.

In view of these results a static extraction time of 15 min was selected. It was also decided to carry out a systematic study of the mutual influence of factors A and E. In this study, experiments were conducted starting from the maximum allowable thimble temperature (120°C) and fixing the density at the maximum level permitted for this temperature. In subsequent experiments, thimble temperature was decreased and, at the same time, the density was systematically increased to the maximum value permitted in each case. Fig. 8 shows the results (mean values of duplicate experiments) obtained for thimble temperatures ranging from 120 to 50°C. It can be seen that 90°C provided maximum extraction yield for all the analytes considered, *m*-cresol showing the most critical behaviour. Below 70°C, extraction yield decreased abruptly for all analytes. Consequently, conditions given in the column on the right in Table 6 were adopted as optimal.

The repeatability and reproducibility of the experimental procedures were evaluated in a

Table 6
SFE parameters and factor levels used in the second (central composite) factorial design, and optimum values for the SFE extraction of phenol and cresols in soils

Factor[a]	Fixed	Low (−)	High (+)	Center	Axial distance	Optimum
CO_2 density (E)		0.65	0.85	0.75	±1.28719	0.77
CO_2 flow	1.5					1.5
Thimble temperature (A)		40	60	50	±1.28719	90
Nozzle temperature	45					45
Trap temperature	20					20
Amount of methanol	50					50
Static extraction time (B)		5	20	12.5	±1.28719	15
Contact time before extraction	0					0

[a] Units in Table 4.

Table 7
Design matrix and response values in the second (central composite) factorial design

Run	Factor A	Factor B	Factor E	Recovery (%)			
				Phenol	*o*-Cresol	*m*-Cresol	*p*-Cresol
1	0	0	0	44.6	58.5	53.3	53.8
2	0	−1.28719	0	31.9	41.4	35.2	35.3
3	−	−	−	31.1	44.9	35.5	35.4
4	+	−	−	42.9	55.4	47.6	49.9
5	+	−	+	60.9	74.3	68.4	71.5
6	0	0	−1.28719	39.2	56.3	46.0	47.9
7	−	+	−	27.8	42.7	30.5	32.5
8	−1.28719	0	0	33.9	47.9	40.8	41.2
9	+	+	+	50.8	67.4	62.6	65.8
10	+1.28719	0	0	57.5	66.5	64.3	65.0
11	−	+	+	44.2	58.8	52.5	54.3
12	0	0	+1.28719	46.7	60.0	57.9	56.3
13	+	+	−	51.8	61.0	58.9	60.3
14	−	−	+	28.2	39.74	34.52	33.9
15	0	+1.28719	0	40.8	61.54	50.54	50.7
16	0	0	0	49.2	65.05	59.70	63.0

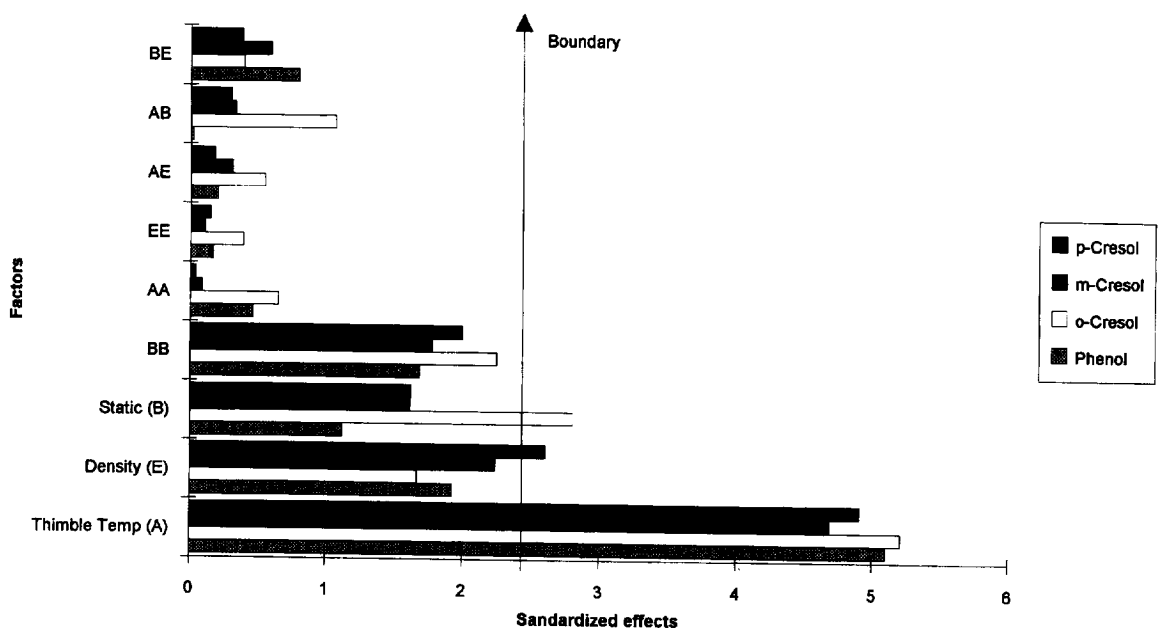

Fig. 6. Pareto chart of standardized effects for the second factor design (central composite model). The vertical line indicates the statistical significance bound for the effects.

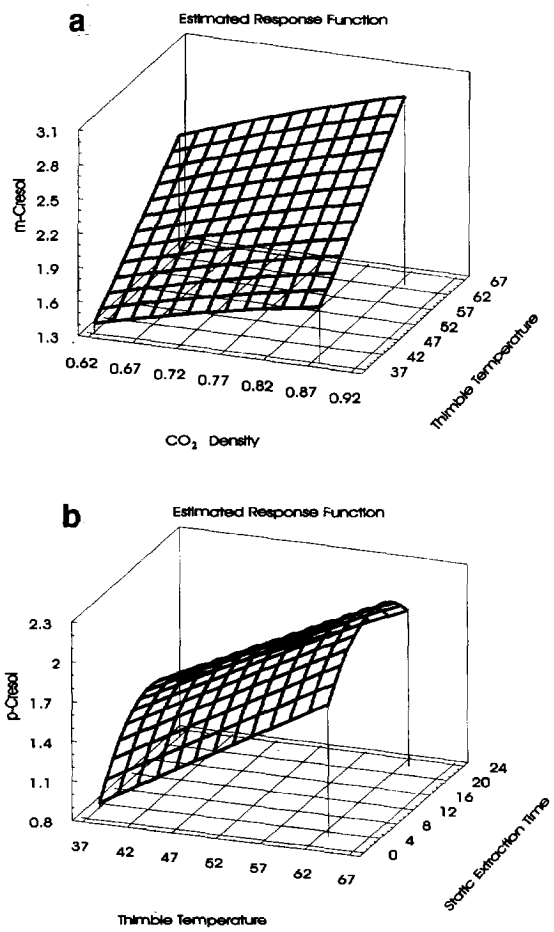

Fig. 7. Response surface estimated from the second factor design: (a) density–thimble temperature; (b) thimble temperature–static extraction time.

series of six consecutive extractions performed on the same day and another six which were carried out on different dates. All these extractions were carried out using the laboratory-spiked soil. Average recoveries obtained are summarised in Table 8. Finally, recoveries were validated by means of a series of extractions from a certified reference material (ERA soil, Lot no. 329). Average recoveries obtained in these experiments are also included in Table 8. It should be noted that this reference material (which, in fact, is certified on the basis of the spiked amounts of analytes and not by means of intercomparison analysis rounds), showed an evident heterogeneous particle size distribution. Thus, extractions were carried out on a portion of this material ground to ca. 60 μm particle size. Apparently, the soil (unknown, in fact, in the case of ERA soil) characteristics of both materials influence the recoveries obtained and thus, a fine tune optimization process when changing soil characteristics is needed. The very low recovery obtained in the case of *o*-cresol is noticeable. This low recovery is in contrast to the excellent recoveries produced by the laboratory spiked soil. Differences in recoveries for phenol and *m*-cresol in both materials appear rather consistent (ca. 10%). Consequently, the low recovery of *o*-cresol cannot be justified on the basis of the different characteristics of soils. However, we have found that other authors [21], who have recently published data regarding other extraction methods using this certified material, from a different Lot number, also found very low recoveries for *o*-cresol (ca. 34%). However, no evidence has been obtained, this led us to be somewhat suspicious about the stability of the spiked *o*-cresol in ERA soil material.

Table 8
Mean recoveries (%) and precision data for laboratory-spiked and ERA soil, Lot No. 329, materials

Compound	Laboratory-spiked soil		ERA soil Lot no. 329
	Repeatability	Reproducibility	
Phenol	90.6 ± 4.0	93.1 ± 4.2	80.7 ± 8.7
o-Cresol	97.9 ± 3.3	99.1 ± 3.6	17.7 ± 9.2
m-Cresol	80.5 ± 6.7	81.9 ± 7.8	69.2 ± 7.5
p-Cresol	76.3 ± 5.5	77.9 ± 6.0	–

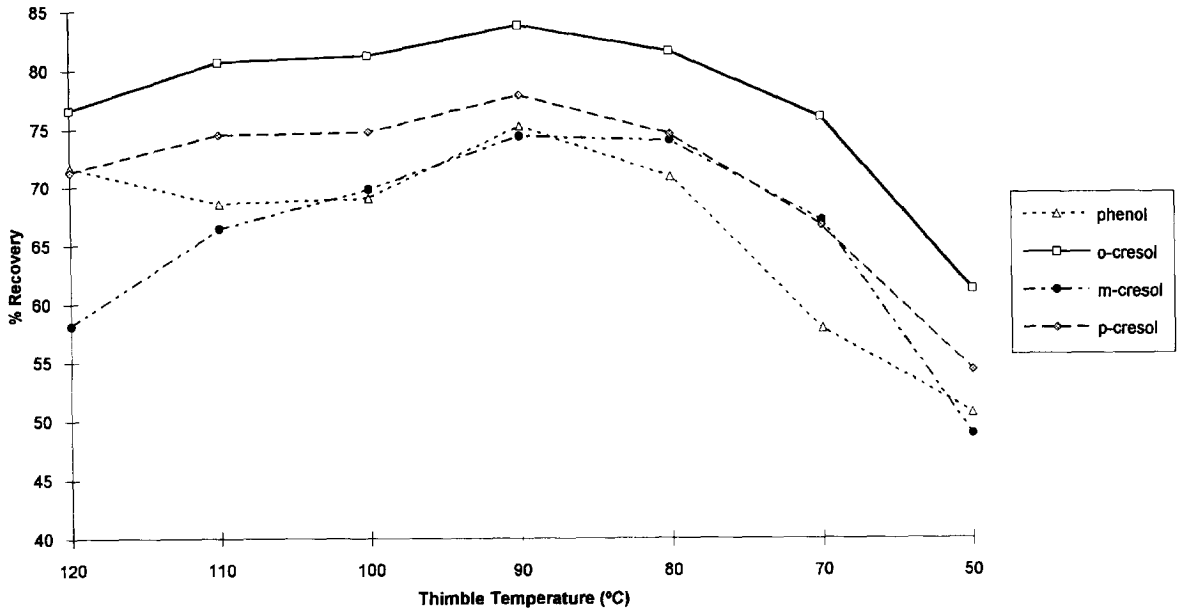

Fig. 8. Evaluation of the optimum thimble temperature value for the SFE of phenol and cresols in soils.

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