

Influence of ligand functionalization of UiO-66-based metal-organic frameworks when used as sorbents in dispersive solid-phase analytical microextraction for different aqueous organic pollutants

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Abstract

Four MOFs, specifically UiO-66, UiO-66-NH₂, UiO-66-NO₂, and MIL-53(Al), were synthesized, characterized, and used as sorbents in a dispersive micro-solid phase extraction (D- μ SPE) method for the determination of nine pollutants of different nature, including drugs, phenols, polycyclic aromatic hydrocarbons, and personal care products in environmental waters. The D- μ SPE method, using these MOFs as sorbents and in combination with high-performance liquid chromatography (HPLC) and diode array detection (DAD), was optimized. The optimization study pointed out to UiO-66-NO₂ as the best MOF to use in the multi-component determination. Furthermore, the utilization of isorecticular MOFs based on UiO-66 with the same topology but different functional groups, and MIL-53(Al) to compare with, allowed us (for the first time) to evaluate the influence of such functionalization of the ligand with regards to the efficiency of the D- μ SPE-HPLC-DAD method. Optimum conditions included: 20 mg of UiO-66-NO₂ MOF in 20 mL of the aqueous sample, 3 min of agitation by vortex and 5 min of centrifugation, followed by the use of only 500 μ L of acetonitrile as desorption solvent (once the MOF containing analytes was separated), 5 min of vortex and 5 min of centrifugation. The validation of the D- μ SPE-HPLC-DAD method showed limits of detection down to 1.5 ng·L⁻¹, average relative recoveries of 107% for a spiked level of 1.5 μ g·L⁻¹, and inter-day precision values with relative standard deviations lower than 14%, for the group of pollutants considered.

Keywords: metal-organic frameworks; dispersive solid-phase extraction; organic pollutants; analyte partitioning

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1. Introduction

Micro- and mesoporous materials are widespread used for separation and purification purposes due to their excellent adsorption properties. Among these porous materials, metal-organic frameworks (MOFs) have received much attention in the last years due to their unique properties: ordered porous structures, the highest surface areas known and even the possibility of tuning their physicochemical behavior [1]. MOFs are three dimensional porous hybrid materials composed by two main building blocks, metal ions as nodes or connectors and organic molecules as linkers, and the combination of these building units offers a limitless number of possible structures [2]. Thus, MOFs have been included as fashion materials in a wide variety of applications, such as gas storage, catalysis, drug delivery or luminescence sensing, among others [3]. Even so, a great number of concerns still exist surrounding stability and synthesis of MOFs [4], despite the fact that nowadays many MOFs have shown excellent stability under harsh conditions [5] and were able to be synthesized on large scales [6].

The use of MOFs as advanced porous materials for more effective and efficient capture of pollutants from different environmental media is increasing in recent years [7]. An important feature of MOFs, which offers a method to satisfy the adsorbent selection criteria, is the modular nature of the organic linker. The design and modification of MOFs at the molecular level can be achieved generally functionalizing the pore surface. This concept of precise control at the molecular level is probably the most distinguishing characteristic of MOFs as compared to other sorbent materials because they can offer additional adsorption sites and also improve the selectivity of pristine MOFs [8].

The well-known MOF UiO-66 (UiO = University of Oslo) [9] exhibits exceptional thermal and chemical stability in water and organic solvents, while presenting good adsorption properties [10]. Several studies have already shown the feasibility of functionalizing the UiO-66 material without losing the physicochemical properties of the parent framework, and mainly

their advantages in gas capture and gas separation have been analyzed [11]. UiO-66 has shown promising adsorption capacities for organic contaminants such as organic dyes [12] and for inorganic pollutants such as heavy metals [13]. However, the adsorption behavior of emerging pollutants, such as pharmaceutical and personal care products on UiO-66 has been scarcely studied [14], and to the best of our knowledge, there are not studies dealing with functionalized UiO-66 materials in microextraction.

Investigations of MOFs in analytical chemistry are rising [15-18]. Thus, Zhou *et al.* reported the first example of MOFs used in analytical chemistry [19], using them in an on-line solid phase extraction (SPE) method. Since then, a variety of MOFs coming from the most widely known families have been tested so far in a number of analytical SPE applications [15,16,18,20] and even in chromatography [17]. The dispersive mode of the miniaturized solid-phase extraction method (D- μ SPE) is a successful approach widely used in sample preparation given its simplicity [21]. It requires a strong dispersion of the sorbent (in an amount lower than 500 mg) into an aqueous sample containing analytes (i.e. with the aid of vortex or ultrasounds), followed by proper separation of the sorbent containing extracted analytes from the sample, and further elution/desorption of trapped analytes before the chromatographic determination [16,21,22].

It is important mentioning that, while existing an increasing number of studies with MOFs as sorbents in D- μ SPE [16], few authors have paid close attention to study the nature of the interactions established between the MOF sorbent and the contaminants. Indeed, the type of interactions that take place during the extraction has not been established completely [14,23,24]. Thus, Rocío-Bautista *et al.* evaluated the partitioning of target compounds to different MOFs in D- μ SPE [24]. The study highlighted the complexity in achieving adequate predictions for the microextraction performance, with successful results mainly linked to the pore environment, pore size, and pore aperture widths of the MOF, together with a clear influence of the metal nature. The nature of the metal of the MOF and its influence in extraction

studies have also been quite recently pointed out by Lirio *et al.* [14], with high importance given to the radius of the metal.

In this sense, the present study evaluates the analytical performance in D- μ SPE of UiO-66 and its derivatives UiO-66-NO₂ and UiO-66-NH₂: with the organic linker functionalized with nitro and amino groups, respectively, but maintaining the isoreticular network. The amino (-NH₂) and nitro (-NO₂) functional groups were chosen to be representative of polar and hydrophilic functionalities. This linker functionalization produces changes in the physicochemical properties of the frameworks with the purpose of establishing stronger host-guest interactions [25], but it also implies a decrease in surface areas and pore volumes [26]. The MOF MIL-53(Al) is used in this study as a comparative material. The application is devoted to the determination of several water contaminants (of quite different nature) using high-performance liquid chromatography (HPLC) and diode-array detection (DAD), intending a multi-component determination while trying to give insights on the influence of the ligand functionality on the possible interactions MOF-target contaminant favoring the entire D- μ SPE-HPLC-DAD method.

2. Experimental

2.1. Chemicals, reagents and materials

Nine analytes of different nature were studied. Carbamazepine (Cbz, 99.0%), 4-cumylphenol (CuP, 99%), 4-*tert*-octylphenol (*t*-OP, 97%), 4-octylphenol (OP, 99%), benzophenone-3 (BP-3, 99.5%) and chrysene (Chy, 98%) were obtained from Sigma-Aldrich (Steinheim, Germany); and progesterone (Pg, >99.99%) was purchased from US Pharmacopeia Reference Standards (Basel, Switzerland). All these compounds were obtained as solid products. A standard solution containing these compounds was prepared in acetonitrile (ACN)

Chromasolv™ liquid chromatography (LC) grade, by Honeywell (Seelze, Germany), at a concentration of $100 \text{ mg}\cdot\text{L}^{-1}$, and stored at $4 \text{ }^\circ\text{C}$. Indeno(1,2,3-cd)pyrene (Ind) and triclosan (Tr) were purchased individually as standard solutions, with a concentration of $10 \text{ mg}\cdot\text{L}^{-1}$ in acetonitrile (ACN) by Dr. Ehrenstorfer GmbH (Augsburg, Germany). Working standard solutions were prepared by dilution in ultrapure water of these standard solutions, with concentrations dependent on the specific experiment. Table S1 of the Electronic Supplementary Material (ESM) shows several characteristics and the structures of the analytes studied.

Ultrapure water (Milli-Q, ultrapure grade) was obtained by a water purification system A10 MilliPore (Watford, UK). Methanol Chromasolv® (LC grade) was purchased to Sigma-Aldrich. HPLC mobile phases were prepared with ultrapure water and ACN Chromasolv™ LC-MS grade. Both phases were filtered with Durapore® membrane filters of $0.45 \text{ }\mu\text{m}$, supplied by Sigma-Aldrich.

$0.2 \text{ }\mu\text{m}$ polyvinylidene fluoride (PVDF) syringe filters Whatman™ were purchased from GE Healthcare (Buckinghamshire, UK), and used to filter all eluates and standards before HPLC injection.

Pyrex® centrifuge tubes (Staffordshire, UK) were used in the microextraction procedure, with dimensions of $10 \times 2.6 \text{ cm}$ and a volume of 25 mL .

Parr Instrument Company (Moline, IL, USA) supplied Teflon solvothermal reactors and stainless steel autoclaves, which were used in the synthesis of the MOFs.

Zirconium chloride (ZrCl_4 , 98%), aluminum(III) nitrate nonahydrate ($\text{Al}(\text{NO}_3)_3\cdot 9\text{H}_2\text{O}$, >99.99%), HCl (37%, v/v), 1,4-benzenedicarboxylic acid (H_2BDC , 98%), 2-amino-1,4-benzenedicarboxylic acid ($\text{NH}_2\text{-H}_2\text{BDC}$, 99%) and 2-nitro-1,4-dicarboxylic acid ($\text{NO}_2\text{-H}_2\text{BDC}$, $\geq 99\%$) were purchased from Sigma-Aldrich and used in the synthesis of MOFs. The solvents used in the synthesis and washing of MOFs include: dimethylformamide (DMF, $\geq 99.5\%$), acquired to Merck KGaA (Darmstadt, Germany), and methanol ($\geq 99.8\%$) purchased from PanReac AppliChem (Barcelona, Spain).

Tap water was taken at the laboratory. Two wastewater samples were supplied by an environmental monitoring laboratory. They were sampled in different areas of Tenerife Island (Canary Islands, Spain) using amber glass recipients properly cleaned, avoiding the formation of bubbles during sampling. They were kept in fridge until reaching the laboratory, and then they were filtered through 0.45 μm filters and kept in the dark at 4 $^{\circ}\text{C}$ until analysis.

2.2. Synthesis of MOFs

The MOFs used in this study were synthesized according to the procedure reported by Katz *et al.* [27]. A standard upscale synthesis of UiO-66 was performed by dissolving 233 mg of ZrCl_4 (1 mmol) and 246 mg of H_2BDC (1.5 mmol) in 15 mL of DMF and 1 mL of concentrated HCl. The resulting mixture was heated in a solvothermal reactor at 150 $^{\circ}\text{C}$ for 24 h. After the solution was cooled to room temperature, the resulting solid was filtered and repeatedly washed with DMF, methanol, and heated at 150 $^{\circ}\text{C}$ for 24 h in order to remove guest molecules from the pores of the crystalline structure. UiO-66- NH_2 and UiO-66- NO_2 MOFs were synthesized analogously by replacing H_2BDC with the equivalent molar amounts of NH_2 - H_2BDC and NO_2 - H_2BDC , respectively.

MIL-53(Al) was prepared according to Loiseau *et al.* [28]. Briefly, 288 mg of H_2BDC (1.7 mmol) and 1.3 g of $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ (3.5 mmol) were mixed in a solvothermal reactor using 15 mL of ultrapure water. The solution was then heated at 220 $^{\circ}\text{C}$ for 3 days. Afterwards, the autoclave was cooled down to room temperature and the obtained white product was isolated by filtration, washed with water, and air-dried at 50 $^{\circ}\text{C}$. The MOF was finally heated at 400 $^{\circ}\text{C}$ during 16 h for the activation.

All synthetic conditions and obtained yields for the MOFs are summarized in Table 1.

2.3. Instruments and equipment

The HPLC used in the determination was a 1260 Infinity model purchased from Agilent Technologies (Santa Clara, CA, USA), in combination with a DAD 1260 Infinity model also from Agilent Technologies. The quantification wavelengths of the DAD were set at 240 nm for Pg, 254 nm for Ind, 270 nm for Chy, 280 nm for CuP, *t*-OP and OP, and 289 nm for Cbz, BP-3 and Tr. The HPLC system includes a Rheodyne injection valve with an injection loop of 20 μ L, supplied by Supelco (Bellefonte, PA, USA). The separation of target analytes was carried out in an ACE Ultra Core 5 SuperC18 (5 μ m, 150 \times 4.6 mm) analytical column, obtained from Symta (Madrid, Spain), with a safeguard column Pelliguard LC-18 purchased to Supelco. ACN and ultrapure water were employed as mobile phases using a linear gradient at a constant flow rate of 1 mL \cdot min⁻¹. The chromatographic method starts at 50% (v/v) of ACN, keeping it constant for 5 min, then increased up to 80% (v/v) in 2 min, then increased up to 83% (v/v) in the next 2.5 min, and finally reaching 100% (v/v) of ACN in the next 3.5 min.

A vortex from Reax-Control HeidolphTM GmbH (Schwabach, Germany) and a centrifuge model 5720 EppendorfTM (Hamburg, Germany) were utilized in the D- μ SPE procedure.

The synthesis of the MOFs was carried out in an oven Universal UF30 model supplied by Memmert (Schwabach, Germany).

Phase identification of all MOFs was carried out by X-ray powder diffraction. A X'Pert Diffractometer supplied by PANalytical (Eindhoven, Netherlands) and operating with Bragg-Brentano geometry was used. Data collection was carried out using Cu K₁ radiation ($\lambda = 1.5418$ Å) over the angular range from 5.01° to 80.00° (0.02° steps) with a total exposure time of 30 min.

An Affinity-1 Fourier transform - infrared (FTIR) spectroscope from Shimadzu (Kyoto, Japan) was used in the identification of the functional groups incorporated to UiO-66.

The nitrogen adsorption isotherms were measured on a Gemini V 2365 Model, supplied by Micromeritics (Georgia, USA), surface area analyzer at 77 K in the range $0.02 \leq P/P_0 \leq 1.00$. The Brunauer, Emmet and Teller (BET) method was used to calculate the surface area.

2.4. Dispersive miniaturized solid-phase extraction procedure (D- μ SPE)

All conditions of the D- μ SPE method using all studied MOFs as sorbents were optimized, including the conditions of both: the extraction and the desorption steps. Under optimum conditions, the extraction is carried out adding 20 mg of UiO-66-NO₂ over 20 mL of water sample (or aqueous standard, depending on the experiment) in a 25 mL Pyrex[®] centrifuge tube. The tube is then subjected to vortex stirring for 3 min, to increase the strength of the interaction between the sorbent and the analytes. Then, the phases are separated by centrifugation ($1921 \times g$ during 5 min) and the supernatant aqueous phase is carefully removed. For the desorption step, 500 μ L of ACN are added to the UiO-66-NO₂ left in the tube containing extracted analytes. Vortex is applied for another 5 min followed by centrifugation during 5 min at $1921 \times g$. The eluate is filtered through 0.2 μ m PVDF syringe filters before being injected in the HPLC.

3. Results and discussion

3.1. Chromatographic method

Contaminants selected in this study include polycyclic aromatic hydrocarbons, drugs, phenols, and personal care products, with the purpose of having a variety of quite different analytes, thus covering different possible interaction mechanisms with the MOFs. The determination of the nine target compounds was carried out using HPLC-DAD, employing

proper quantification wavelengths for each analyte. The optimum conditions for the separation were summarized in Section 2.3, with the overall separation requiring less than 13 minutes, as it can be observed in Figure S1 of the ESM.

Several quality analytical parameters of the calibrations obtained by HPLC-DAD are shown in Table S2 of the ESM. Calibration curves present adequate linearity, with correlation coefficient (R) values higher than 0.9983. The limits of detection (LOD) and the limits of quantification (LOQ) were calculated as the signal to noise (S/N) ratio of 3 and 10, respectively. LOD and LOQ values were verified by preparation of standards at such levels of concentration. LODs varied from $0.02 \mu\text{g}\cdot\text{L}^{-1}$ for Chy to $1.00 \mu\text{g}\cdot\text{L}^{-1}$ for CuP. The precision of the chromatographic method was calculated using three standards at concentration levels not utilized in the calibration curve (but included within the calibration range): $6 \mu\text{g}\cdot\text{L}^{-1}$, $30 \mu\text{g}\cdot\text{L}^{-1}$ and $70 \mu\text{g}\cdot\text{L}^{-1}$ ($n = 5$). The obtained results are included in Table S3 of the ESM. In all cases, relative standard deviations (RSD, in %) values were lower than 3.7% for the lowest concentration level tested and 2.9% for the highest concentration level injected. Regarding the precision of the chromatographic retention times, RSD values were always lower than 0.21% ($n = 15$).

3.2. Synthesis and characterization of studied MOFs

Following an isorecticular synthesis, a family of MOFs based on the UiO-66 structure was obtained from the two different linker ligands: $\text{NH}_2\text{-H}_2\text{BDC}$ and $\text{NO}_2\text{-H}_2\text{BDC}$ [25]. The crystal and particle size of the UiO-66 and UiO-66-X ($X = \text{NH}_2$ and NO_2) materials were controlled by modulated synthesis with HCl (as detailed in Section 2.2 and Table 1). All compounds were obtained in high yields without loss of crystallinity or porosity by including HCl in the reaction mixtures during the synthesis.

The X ray diffraction patterns obtained for the as-synthesized samples (see Figures S2 and S3 of the ESM) revealed that the materials are crystalline and the two functionalized compounds are isostructural with the parent material UiO-66, which demonstrates that the tagged UiO-66-X MOFs are topologically equivalent with UiO-66. It is important to prove this equivalence in order to achieve proper comparison when using these materials as sorbents, to clearly link results to the organic ligand nature.

N₂ adsorption/desorption isotherms were collected at 77 K (Figure S4 of the ESM) and the Brunauer, Emmett and Teller (BET) surface areas were calculated and all the materials were found to retain porosity. The BET surface area data was found to decrease in surface area with the functionalization of the pores, from ~1342 m²·g⁻¹ in the parent UiO-66 to ~794 m²·g⁻¹ for UiO-66-NH₂ and ~771 m²·g⁻¹ for UiO-66-NO₂, and they are in agreement with previous reported values [27].

The presence of the functional groups on the linkers was further evidenced by characterizing the MOFs with FTIR spectroscopy (Figure S5 of the ESM). Thus, UiO-66-NH₂ displays a broad absorption band at 3336 cm⁻¹ that is assigned to the N-H stretching modes. A band at 1546 cm⁻¹ and a band at 1389 cm⁻¹ are attributed respectively, to the asymmetric ($\nu(\text{NO})_{\text{asym}}$) and symmetric ($\nu(\text{NO})_{\text{sym}}$) stretching modes of the nitro group in UiO-66-NO₂.

MIL-53(Al) was used in this study for comparative purposes, because it has previously demonstrated its successful performance as sorbent in D- μ SPE. The diffraction pattern (Figure S3 of the ESM) shows that the synthesized compound presents the crystal structure of MIL53(Al) and the calculated Brunauer, Emmett and Teller (BET) surface area is in agreement with the reported value [24].

3.3. Screening of MOFs as sorbents in D- μ SPE-HPLC-DAD

D- μ SPE was selected as microextraction approach in this study given its simplicity and high analytical performance [16]. An initial screening study was carried out in order to study the microextraction performance of UiO-66, UiO-66-NH₂ and UiO-66-NO₂ in the D- μ SPE of target contaminants. Main difference among these MOFs, as above-mentioned in the characterization study, is the nature of the organic ligand, having all the same topology and quite similar surface areas. In this screening study, the MOF MIL-53(Al) was also included in the comparison for having been pointed out as adequate sorbent in common microextraction applications of similar analytes [24].

The D- μ SPE method was initially performed with common extraction conditions. Thus, low amounts of MOF were used to fulfil microextraction requirements, minimization of costs, and proper environmental goals. The analytes, once trapped by the MOF, were desorbed using ACN as elution solvent, for being compatible with the HPLC mobile phases used. In this sense, the initial working conditions included 20 mg of MOF, 20 mL of an aqueous standard (containing all analytes at a concentration level of 5.00 $\mu\text{g}\cdot\text{L}^{-1}$), 5 min of vortex agitation, and 5 min of centrifugation (at $1921 \times g$). Afterwards, the supernatant was discarded and 0.500 mL (to avoid losses of preconcentration during the process) of ACN were added as elution solvent, followed by 5 min of vortex and 5 min of centrifugation (at $1921 \times g$).

Results obtained under these conditions revealed that UiO-66-NO₂ presented adequate extraction efficiencies for many analytes, and that in practically all cases (only excluding CuP), MIL-53(Al) was not the best MOF to be chosen as sorbent despite previous studies [24]. Therefore, we used the information obtained from this screening study to optimize the entire D- μ SPE-HPLC-DAD method using UiO-66-NO₂ as sorbent.

3.4. Optimization of the D- μ SPE-HPLC-DAD method using UiO-66-NO₂

The D- μ SPE-HPLC-DAD method with UiO-66-NO₂ was optimized having as targets the maximization of the extraction efficiency for the highest number of possible of contaminants, and the minimization of the amount of MOF and solvents in the procedure. Main variables studied in the one-factor-at a time optimization of the method were: amount of MOF sorbent, extraction and elution time, number of elution steps and nature of the elution solvent.

The first variable optimized was the amount of UiO-66-NO₂, with tested values ranging between 10 and 30 mg. These studies were carried out with aqueous standards (10.0 $\mu\text{g}\cdot\text{L}^{-1}$ of Cbz, Tr and *t*-OP, and 2.50 $\mu\text{g}\cdot\text{L}^{-1}$ for the rest of analytes), and the remaining conditions already fixed during the screening (Section 3.3). Figure 1 shows the results obtained monitoring the extraction efficiencies in terms of peak areas. In general, best results were obtained when using 10 or 20 mg of UiO-66-NO₂, without significant differences in the performance among them, except for Pg, which achieved much better results when using 20 mg. For this reason, 20 mg was selected as the optimum amount of UiO-66-NO₂.

The second variable considered in this optimization was the extraction time, with the extraction step assisted by vortex, utilizing times between 1 and 5 min. Vortex times higher than 5 min are not advisable and thus were not tested. These experiments were performed using 20 mg of MOF, and the fixed conditions above mentioned. Figure S6 of the ESM shows the obtained results, which clearly point out to 3 min as the optimum value.

The third variable included in the optimization was the elution time, also assisted by vortex, with times also varying between 1 and 5 min, using as fixed conditions: 20 mg of MOF, 3 min for the vortex-assisted extraction time, and the remaining conditions fixed as in previous experiments. Figure S7 of the ESM shows clear improvements in the elution with longer times, and thus 5 min was selected as the optimum.

The elution step in D- μ SPE with MOFs has been pointed out as the critical step to achieve adequate analytical performance [29]. Therefore, the number of elution steps and the nature of the elution solvent were also considered in this optimization. Regarding the number

of elution steps, it was evaluated the use of two elution steps (each one with 0.250 mL of ACN) *versus* the use of one single elution step (0.500 mL of ACN). It can be observed from Figure S8 of the ESM the absence of significant improvements when increasing the number of elution steps. Therefore, one single elution step was preferred. This also permits a decrease in the overall analysis time, which is advisable. Regarding the nature of the elution solvent, different solvents (compatible with HPLC mobile phases) were compared: ACN, methanol, and acetone; using all already optimized conditions of the method. Results (included in Figure S9 of the ESM) point out the adequacy of ACN.

A summary of the entire optimized D- μ SPE-HPLC-DAD method is included in Figure 2.

3.5. Influence of the UiO-66 ligand functionalization in the overall efficiency of the D- μ SPE-HPLC-DAD method

After completion of the optimization, the D- μ SPE-HPLC-DAD method was carried out using UiO-66, UiO-66 derivatives, and MIL-53(Al) as sorbents. The E_R values obtained for the target analytes with the different MOFs are included in Figure 3. Results revealed that UiO-66-NO₂ was the best MOF as sorbent for 7 out of the 9 contaminants studied, and thus it can be considered a generic sorbent if intending a multi-component determination.

Nevertheless, apart for the importance of utilizing this MOF to set up a multi-component monitoring method through D- μ SPE, the obtained results are highly valuable in order to get understanding on the nature of possible interactions MOFs-analytes. However, one should keep in mind that the E_R values refer to the complete microextraction method, comprising two steps: the adsorption of the analytes by the MOF extractant and the elution/desorption process. Therefore, the affinity of the MOF for a particular analyte can not be made exclusively based

on the E_R value, since this evaluate a complete process in which desorption readiness (weak analyte-MOF interaction) is favored.

In general, the results introduced in this study indicate that the functionalization by means of polar groups is a noteworthy factor affecting positively the total efficiency of the method (understood as extraction/elution process ability) for the studied analytes of quite different nature. This result shows that the reduction in effective pore size by functional groups is not critical in the analytical procedure, since the electronic properties of these groups favor the analyte-MOF interaction. The UiO-66 has a moderate pore window size of around 7 Å in diameter and moderate pore size diameter of 11 Å, whereas the UiO-66-X variants reduce the window opening and pore sizes [30]. This implies that the pore window size is large enough for small molecules, but the bulkier ones may have hindering problems and they most likely interact with the MOF surface.

Two adsorption sites for pollutants molecules can be distinguished in the UiO-66-X family, the $Zr_6O_4(OH)_4$ cluster, a hydrophilic area where water, acetic acid and other groups can be coordinated in some MOFs [31]; and the ligand environment which changes from the more hydrophobic $X = H$ to the more hydrophilic $X = NH_2$ or NO_2 . The adsorption mechanisms may include hydrophobic effects, π - π electron donor-acceptor interactions, electrostatic attractions, [32] or even stronger interactions such as chemical bond or hydrogen bond [33,34].

Analytes accessing the pores window will have a strong interaction with the inside pore walls, which probably improve the extraction step but at the same time, makes more difficult the elution step. The host voids in functionalized materials can act as a “tweezer”, providing suitable electronic environments to trap the guest molecules [8]. The moderate pore size will make the adsorbed molecules have a closer distance and stronger interactions with the inside pore walls, thus making difficult the elution process with organic eluents. Therefore, we cannot conclude that higher real recovery values listed in Figure 3 necessarily imply better analyte-

MOF interactions, they just represent the minimum value of the quantity of analyte adsorbed by the MOF (either at the pores or at the surface).

Considering this, the best extraction performance occurs for the 4-octylphenol with both NH₂- and NO₂-functionalized UiO-66 with E_R values larger than 60%, and in general, UiO-66-NO₂ seems to be the best extractant material as remarked before. The influence of the narrower pore in the decorated UiO-66 MOFs can be observed in the trend for the three phenols analyzed. They follow a trend where the 4-cumylphenol (CuP) is the bulkier, followed by the 4-tert-octylphenol (*t*-OP) and the 4-octylphenol (OP). The E_R values for the NH₂-UiO-66 and NO₂-UiO-66 follow an inverse trend, OP > *t*-OP > CuP, whilst for the bare UiO-66 and MIL-53(Al) the E_R values are similar (around 40%). One can conclude that for bulkier analytes the adsorption is hindered, and the E_R is reduced.

In general, the functionalized NH₂- and NO₂-UiO-66 MOFs outperform the bare UiO-66 in recovery values. This may be due to various reasons: *i*) The amino -and nitro- decorations as H-bond donor and acceptor groups increase the anchoring sites for guest molecules, and these electron-withdrawing groups could lead to effective adsorption from charge-transfer interactions between the functionalized groups and these guest molecules [35]; *ii*) The more hydrophilic environment in the pore surface caused by the NH₂ and NO₂ groups may promote a better elution with the non-polar organic solvents.

In the case of triclosan (Tr), it seems that a larger number of anchoring sites in the form of H-bond acceptors or donors notably increase the extraction ability of the UiO-66 [36]. This situation is also observed in Figure 3, where both NH₂- and NO₂-UiO-66 outperform bare UiO-66 in the extraction of triclosan, and a similar trend is observed for carbamazepine (Cbz), progesterone (Pg), and benzophenone-3 (BP-3).

In the case of the PAHs included in this analysis, chrysene (Chy) and indeno(1,2,3-cd)pyrene (Ind), the functionalized UiO-66 MOFs also perform better than the bare one. This situation seems contradictory, since more hydrophobic, bulky analytes are being better

recovered by more hydrophilic, narrow pore NH₂- and NO₂-UiO-66 materials. This behavior may be explained taking into account the favored elution process of loosely linked PAHs on the surface of the functionalized MOFs. Probably, these bulky PAHs are adsorbed on the surface of the MOFs and the slightly more hydrophilic environment of the functionalized UiO-66 help in the elution process, and we therefore observe an increase in the total E_R factor. Also, we cannot discard some competitive interactions of the MOFs with the other analytes that lead to a better recovery of the PAHs in this case.

Clearly, to establish relationships between the effects of the functionalization of MOFs on their sorption capacities results a very difficult task, because there are numerous factors to consider [37]. Among them, pore size reduction and molecular sieving effect [38], changes in polar character or electronic environments of the frameworks, energy effects [39] or other factors (such as intrinsic defects, co-adsorption, or diffusive transport in the material pores, as those most remarkable). Moreover, from the point of view of organic pollutants trapped by these sorbents, the physicochemical parameters such as molecular sizes, shapes, polarities, polarizabilities, interaction abilities, solubility, hydrophilicity, acidity and so on, also need consideration. An approach to the fundamental understanding of mechanisms and interactions is highly required for the design of better materials, even selective, for microextraction processes.

3.6. Quality analytical parameters of the optimized D- μ SPE-HPLC-DAD method

The analytical method using D- μ SPE-HPLC-DAD and the MOF UiO-66-NO₂ under the optimized conditions described (Figure 2) was validated. Calibration curves were obtained subjecting aqueous standards to the entire method. Several of the quality analytical parameters obtained are shown in Table 2. Correlation coefficients (R) were higher than 0.9966 in all cases. LODs were calculated as the concentration in the aqueous sample able to generate a signal to

noise ratio of three ($S/N = 3$) after the overall microextraction and chromatographic procedure, and LOQs as ten times signal to noise ratio ($S/N = 10$). LODs and LOQs were verified by preparation of aqueous standards at those levels. Obtained LODs ranged from $1.50 \text{ ng}\cdot\text{L}^{-1}$ for Chy and Ind to $300 \text{ ng}\cdot\text{L}^{-1}$ for CuP and *t*-OP. It is important to highlight the low LODs achieved with the current microextraction method, particularly considering that DAD is used. A comparison with other methods, which also use solid-based dispersion techniques in combination with HPLC-DAD or HPLC-UV, are included in Table S4 of the ESM. Clearly, the current study presents better sensitivity, and it presents the difficulty of dealing with multi-component determination.

The inter-day precision (RSD, in %) of the entire D- μ SPE-HPLC-DAD method was studied, by triplicate, at two spiked levels during 3 non-consecutive days ($n = 3$, intra-day). Table 3 shows that inter-day RSD values ranged from 4.1% for Pg to 14% for Cbz at the lowest spiked level, and from 4.3% for OP to 9.7% for Tr at the highest spiked level. Intra-day RSD values were always lower than 12%.

Average relative recoveries (RR, in %) were of 107% at the lowest spiked level and of 98.0% at the highest spiked level. Real extraction efficiencies (E_R , in %), for the entire D- μ SPE-HPLC-DAD method range from 22.0% for Cbz to 69.6% for OP at the lowest spiked level. Several authors have pointed out the difficulties in reaching E_R values close to 100% in any microextraction procedure. Indeed, E_R values are generally not reported in microextraction studies (see Table S4 of the ESM). In any case, the validity of any E_R value for an analyte in a specific microextraction method is dependent on how sensitive and reproducible is a method for a particular application [16,40].

3.7. Analysis of wastewaters and tap water samples using the optimized D- μ SPE-HPLC-DAD method

One tap water and two wastewaters samples were analyzed using the optimized D- μ SPE-HPLC-DAD method. As it can be observed in Table S5 of the ESM, none of the nine analytes were detected in these samples.

Wastewater-1 was used as blank matrix to perform precision and recovery studies that serve, in addition, to evaluate the matrix effect given its complexity. The obtained results are also shown in Table S5 of the ESM, using a quite low spiked level of $1.5 \mu\text{g}\cdot\text{L}^{-1}$. From the obtained results, there is a clear matrix effect for analytes such as Cbz, Tr and Pg. For this type of samples, matrix-matched calibrations are recommended.

In any case, it is important to mention that the obtained RSD values (in %) were lower than 17%, which is adequate for this microextraction method considering the low spiked level used for the wastewater sample and its complexity.

4. Conclusions

Four MOFs (MIL-53(Al), UiO-66, UiO,66-NH₂ and UiO-66-NO₂) were successfully synthesized, characterized and tested as sorbents for a D- μ SPE method that implies monitoring of nine pollutants of different nature: carbamazepine, 4-cumylphenol, progesterone, benzophenone-3, triclosan, 4-*tert*-octylphenol, 4-octylphenol, chrysene and indeno(1,2,3-cd)pyrene.

The dispersive method in combination with HPLC-DAD was properly optimized using the UiO-66-NO₂ MOF, selected as the sorbent which offers highest extraction efficiencies for seven out of the nine analytes, thus being a generic sorbent for this multi-component determination. Low amounts of MOF (20 mg), low sample volumes (20 mL), short sample preparation times (8 min for extraction and 10 min for desorption, both using vortex), and the minimization of the organic solvent needed in the elution step (500 μL) were the optimum conditions for this microextraction method. Limits of detection down to $1.5 \text{ ng}\cdot\text{L}^{-1}$ were

achieved for Chy and Ind despite using DAD, as well as proper analytical performance results such as adequate recovery, extraction efficiency and inter-day precision.

An insight on the possible interactions established between these MOFs and the studied analytes, as a function of the nature of the functionalization of the organic ligand in the MOF, while keeping constant the remaining topological conditions of the crystals, was given. The total efficiency of the D- μ SPE-HPLC-DAD method was positively influenced by the presence of functionalization groups in the ligands of UiO-66, particularly due to the polar character given to the organic linkers. Nevertheless, not all results can be justified only based on the polar character of the organic linkers. As main factors, it is important to highlight the pore size of a MOF and the molecular sieving effect, changes in the polar character or the electronic environments of the frameworks, energy effects, as well as intrinsic characteristics of analytes experiencing partitioning to the MOFs.

The results of the current study will serve to better design of MOFs to be used as sorbents in D- μ SPE, intending tailored microextractions.

Acknowledgments

V.P. and C.R.-P. thank the MINECO for the Projects Ref. MAT2014-57465-R and MAT2017-89207-R. P.R.-B. thanks her FPI PhD research contract associated to the Project Ref. MAT2014-57465-R. All authors also thank the SEGAI services of the ULL, specially the technicians, for the help provided.

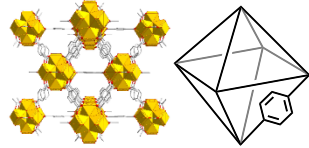
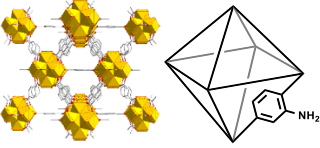
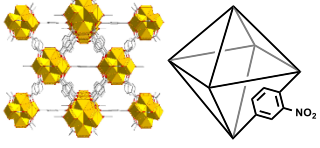

References

- [1] J. Chromatogr. A X (2015) X.

Figure Legends

- Fig. 1** Effect of the amount of UiO-66-NO₂ on the extraction efficiency for all analytes in D- μ SPE-HPLC-DAD. Specific conditions are described in Section 3.4. Experiments were carried out in triplicate.
- Fig. 2.** Scheme of the entire D- μ SPE-HPLC-DAD method using the MOF UiO-66-NO₂ under optimum conditions.
- Fig. 3.** Comparison between the different MOFs used in terms of extraction efficiency with the optimum D- μ SPE-HPLC-DAD method. Fixed optimum conditions as described in the text. Experiments were carried out in triplicate.

Table 1. Synthetic conditions of MOFs and yields obtained.

MOF	Structure (detailed functionalization for UiO-66)	Metal (mg)	Ligand (mg)	Solvent (mL)	Modulator (mL)	Yield (%)
UiO-66		Zr ⁴⁺ (233)	terephthalic acid (246)	DMF (15)	HCl (37%, v/v) (1)	95
UiO-66-NH ₂		Zr ⁴⁺ (233)	2-aminoterephthalic acid (271)	DMF (15)	HCl (37%, v/v) (1)	78
UiO-66-NO ₂		Zr ⁴⁺ (233)	2-nitroterephthalic acid (317)	DMF (15)	HCl (37%, v/v) (1)	97
MIL-53(Al)		Al ³⁺ (1300)	terephthalic acid (288)	H ₂ O (15)	-	45

DMF: dimethylformamide

Table 2. Several quality analytical parameters of the D- μ SPE-HPLC-DAD method.

Analyte	Calibration range ($\mu\text{g}\cdot\text{L}^{-1}$)	R	$s_{y/x}$ ^a	Slope \pm SD ^b	LOD ($\text{ng}\cdot\text{L}^{-1}$)	LOQ ($\text{ng}\cdot\text{L}^{-1}$)
Carbamazepine	0.05 – 5.74	0.9989	0.27	2.3 ± 0.2	5.0	16.7
4-Cumylphenol	0.80 – 5.74	0.9966	0.11	0.5 ± 0.1	90	300
Progesterone	0.01 – 5.74	0.9980	0.99	6.5 ± 0.5	2.4	8.00
Benzophenone-3	0.05 – 5.74	0.9991	0.38	3.8 ± 0.2	4.5	15.0
Triclosan	0.50 – 5.00	0.9982	0.17	1.3 ± 0.1	30	100
4- <i>tert</i> -Octylphenol	0.50 – 4.00	0.9995	0.09	1.8 ± 0.1	90	300
4-Octylphenol	0.10 – 5.00	0.9998	0.10	2.4 ± 0.1	15	50.0
Chrysene	0.01 – 5.74	0.9984	4.8	37 ± 2	1.5	5.00
Indeno(1,2,3- <i>cd</i>)pyrene	0.01 – 5.74	0.9986	1.6	13 ± 1	1.5	5.00

^a standard deviation of the regression (or error of the estimate)

^b confidence intervals for the slope (n = 6) with a signification level of 95%

Table 3. Analytical performance of the entire D- μ SPE-HPLC-DAD method in terms of relative recovery, extraction efficiency, and inter-day precision with aqueous standards.

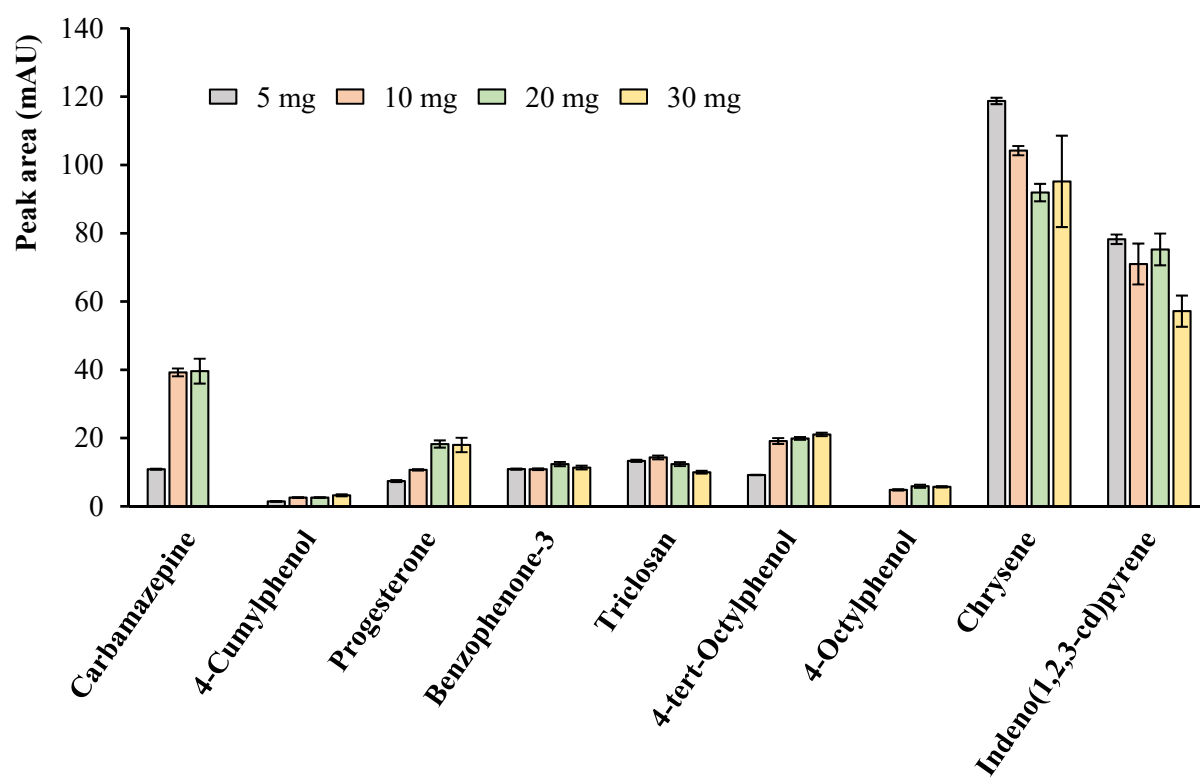
Analyte	Spiked level 1 (1.50 $\mu\text{g}\cdot\text{L}^{-1}$)				Spiked level 2 (4.50 $\mu\text{g}\cdot\text{L}^{-1}$)			
	E_R^a (%)	RR^b (%)	Inter-day RSD ^c (%)	Intra-day RSD range ^d (%)	E_R^a (%)	RR^b (%)	Inter-day RSD ^c (%)	Intra-day RSD range ^d (%)
Carbamazepine	22.0	99.4	14	1.0 – 12	15.6	100	8.8	6.9 – 11
4-Cumylphenol	35.2	126	9.3	4.7 – 8.3	21.1	100	9.6	5.4 – 6.7
Progesterone	51.0	111	4.1	3.3 – 4.4	42.8	88.8	6.7	3.2 – 4.8
Benzophenone-3	29.2	112	9.4	3.2 – 7.7	25.7	91.9	8.1	2.6 – 3.6
Triclosan	40.8	95.0	8.2	5.4 – 9.5	43.0	104	9.7	5.6 – 8.9
4- <i>tert</i> -Octylphenol	53.5	118	7.2	4.1 – 8.2	45.7	102	5.7	2.5 – 3.7
4-Octylphenol	69.6	102	7.5	6.1 – 9.5	63.9	90.5	4.3	1.2 – 2.4
Chrysene	39.4	109	5.5	2.0 – 7.4	43.8	127	8.7	3.3 – 9.6
Indeno(1,2,3- <i>cd</i>)pyrene	27.1	87.3	9.1	4.1 – 8.4	24.3	79.2	6.3	2.9 – 5.9

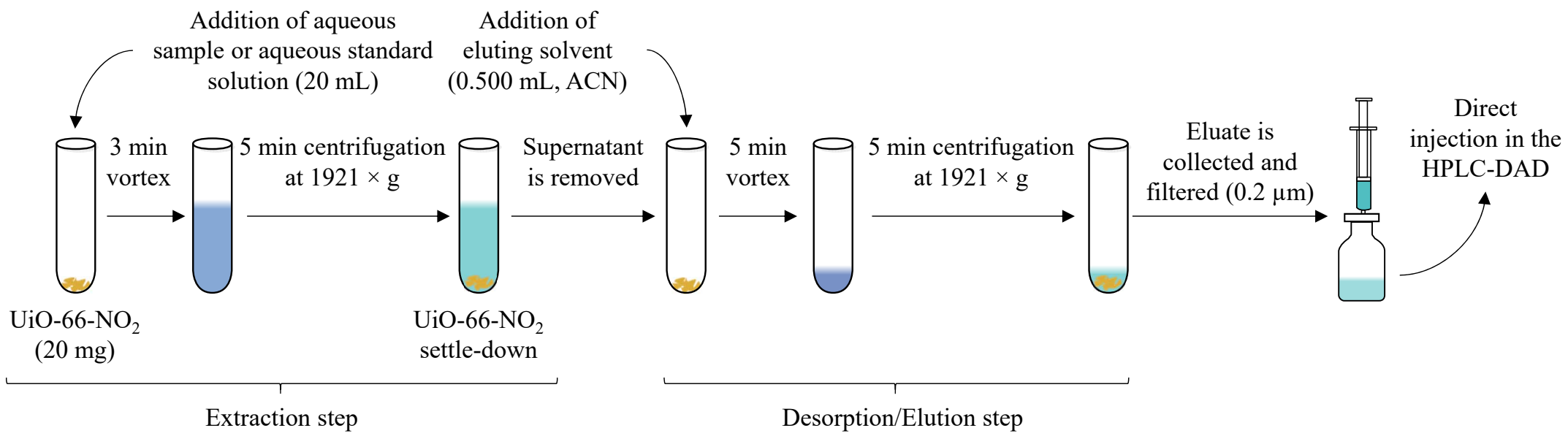
^a extraction efficiency calculated considering the preconcentration achieved with the microextraction method

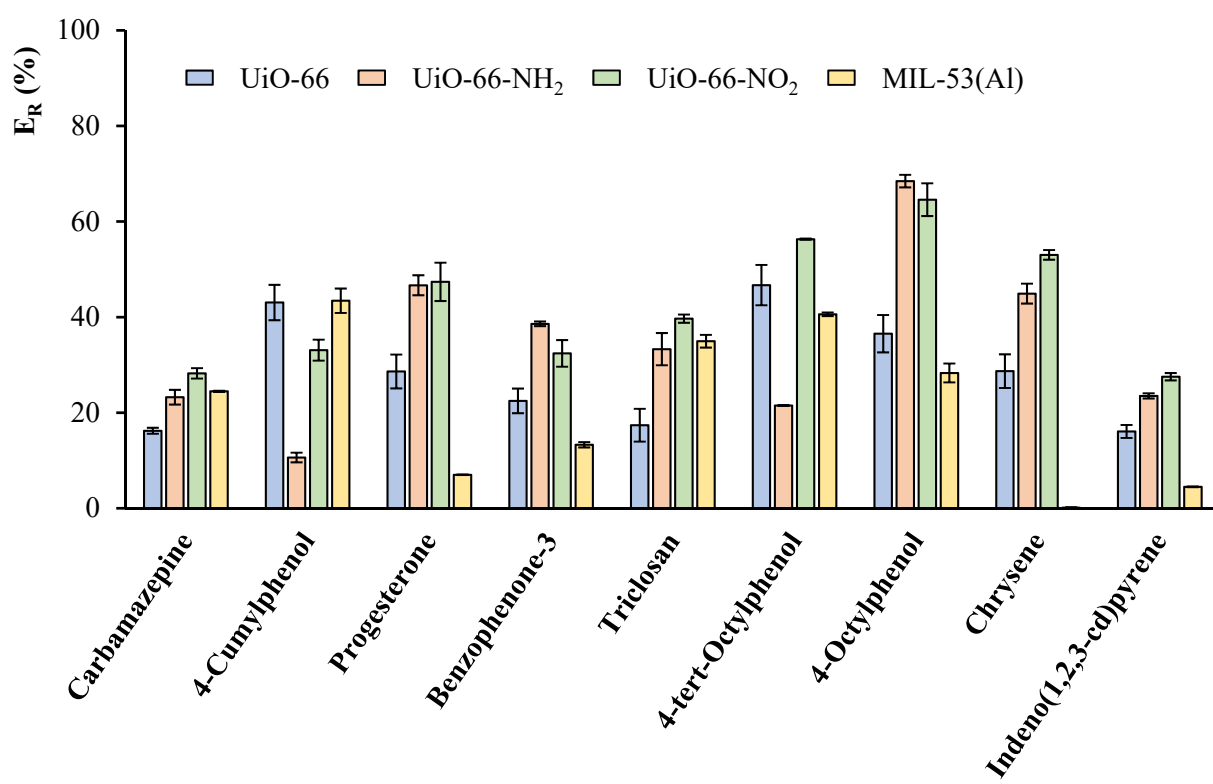
^b relative recovery

^c relative standard deviation for the inter-day precision (n = 9, 3 non-consecutive days)

^d intra-day relative standard deviation range (n = 3)







Supplementary Material

Influence of ligand functionalization of UiO-66-based metal-organic frameworks when used as sorbents in dispersive solid-phase analytical microextraction for different aqueous organic pollutants

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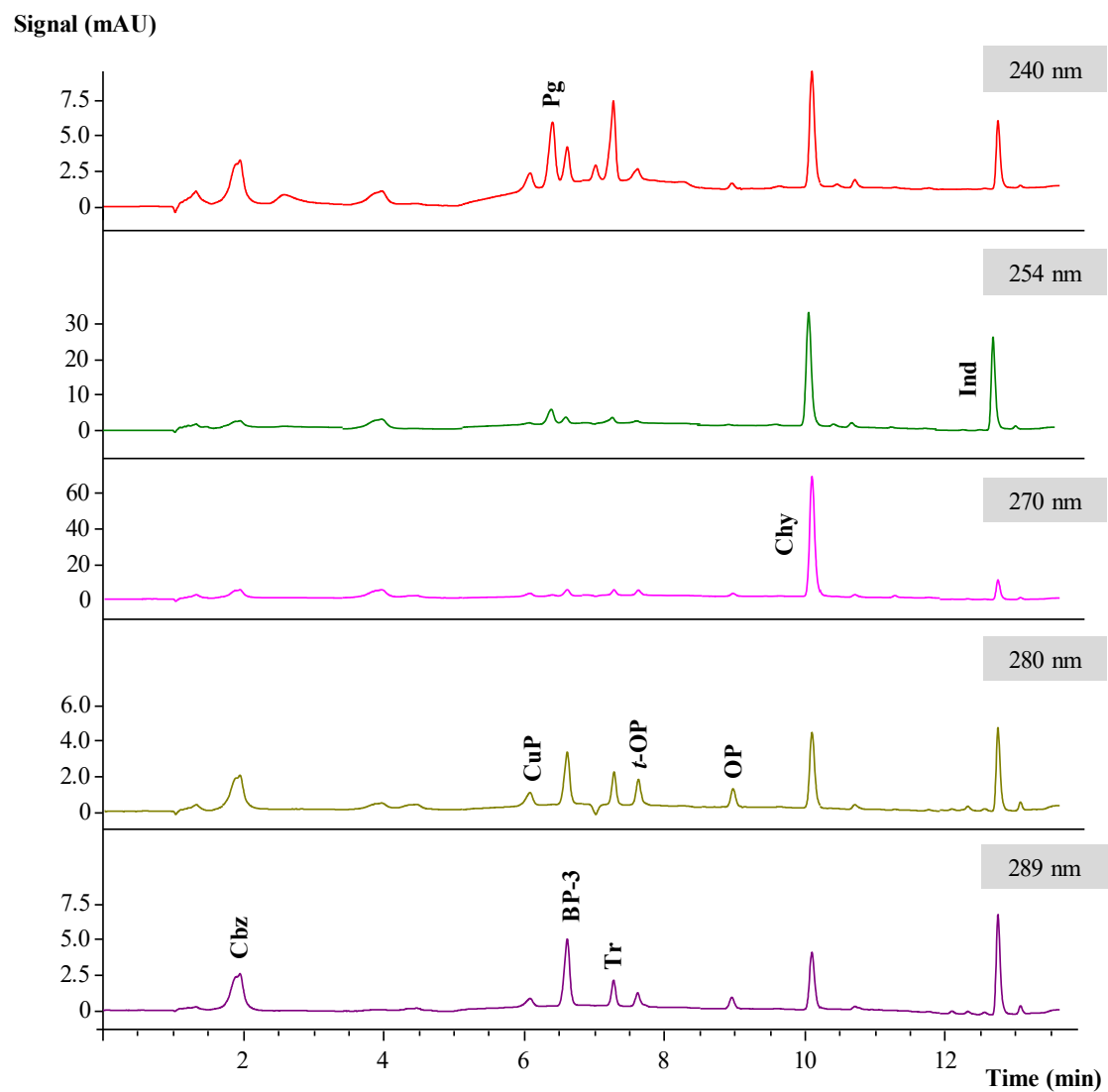


Figure S1. Representative chromatogram of a standard ($100 \mu\text{g}\cdot\text{L}^{-1}$) containing all analytes.

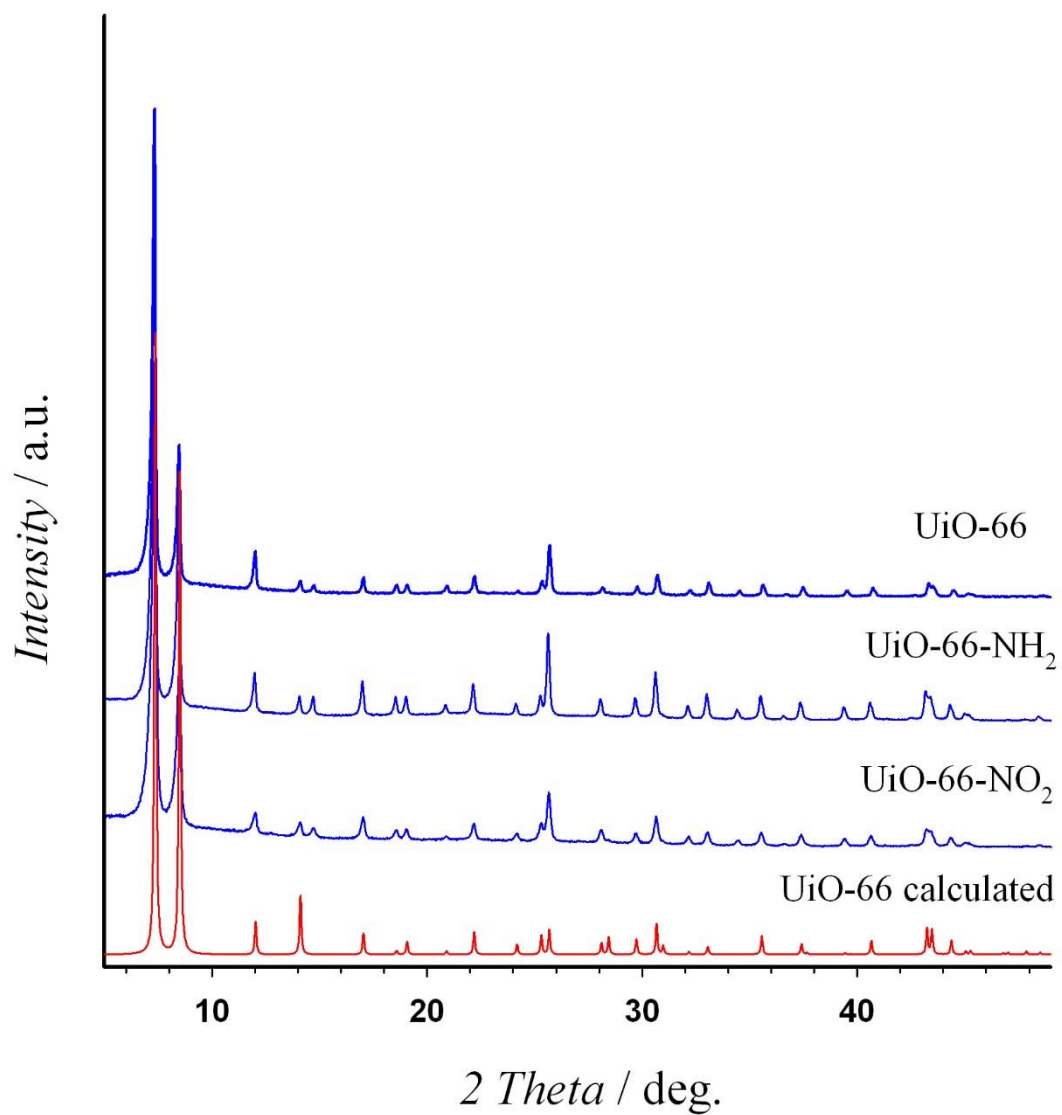


Figure S2. XRD patterns of UiO-66, UiO-66-NO₂ and UiO-66-NH₂ MOFs.

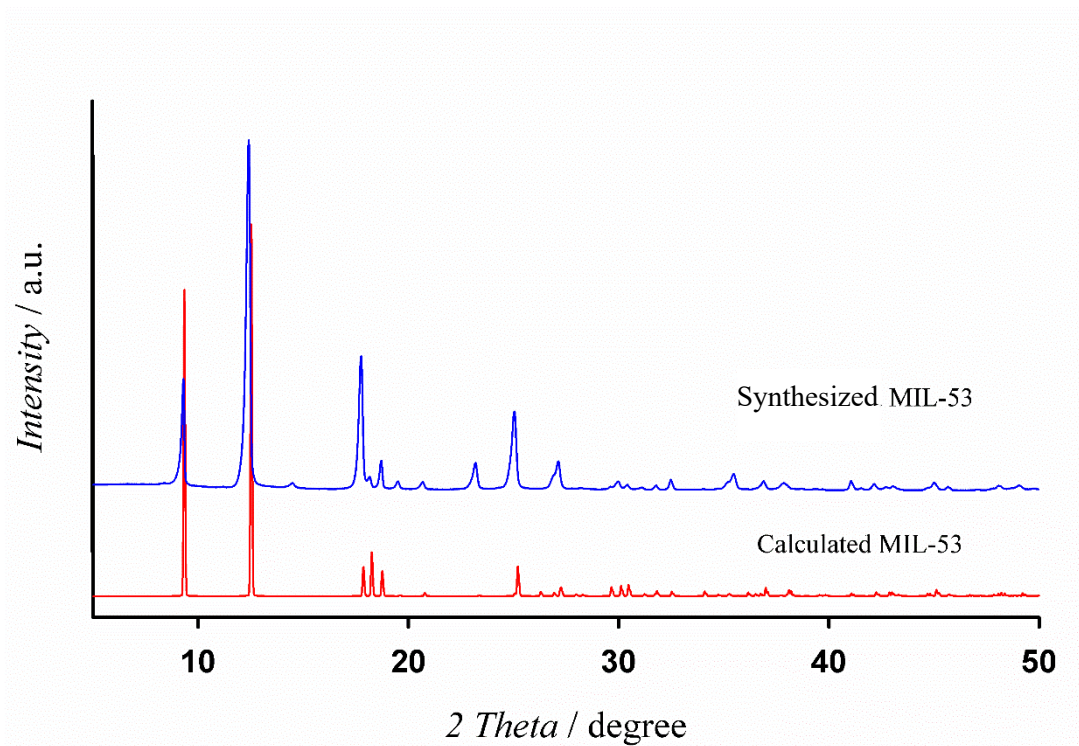


Figure S3. XRD patterns of MIL-53(AI) MOF.

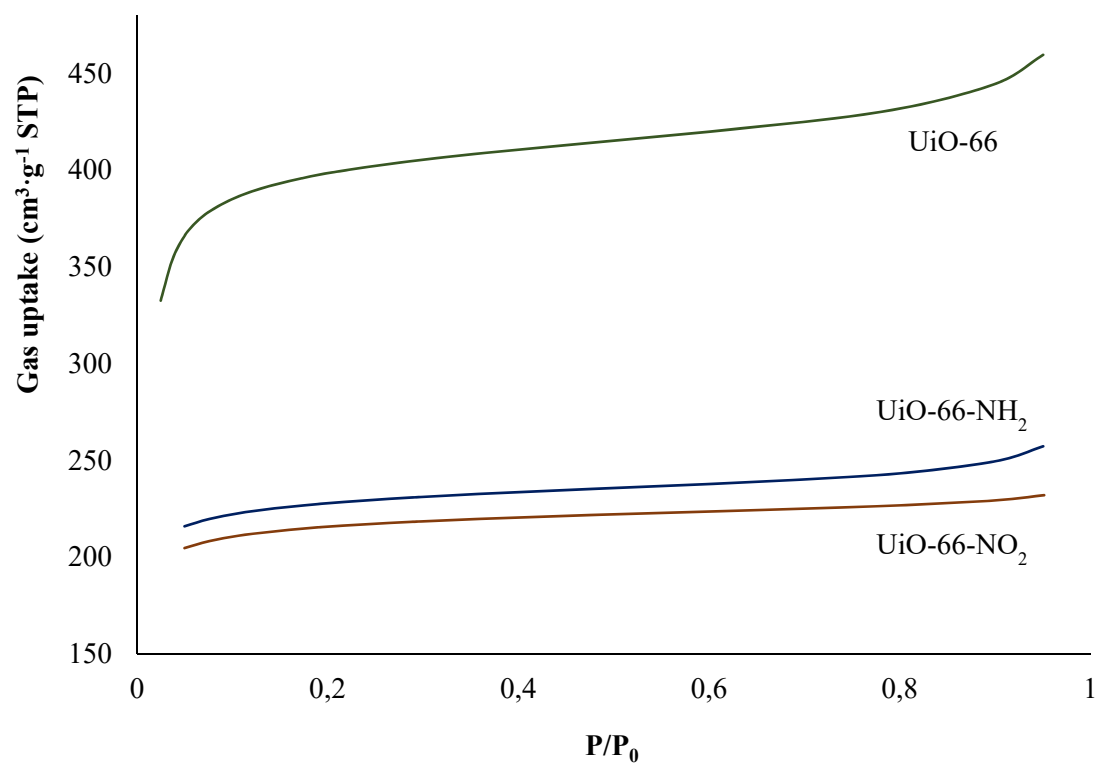


Figure S4. Nitrogen adsorption/desorption isotherms of UiO-66, UiO-66-NH₂ and UiO-66-NO₂ MOFs.

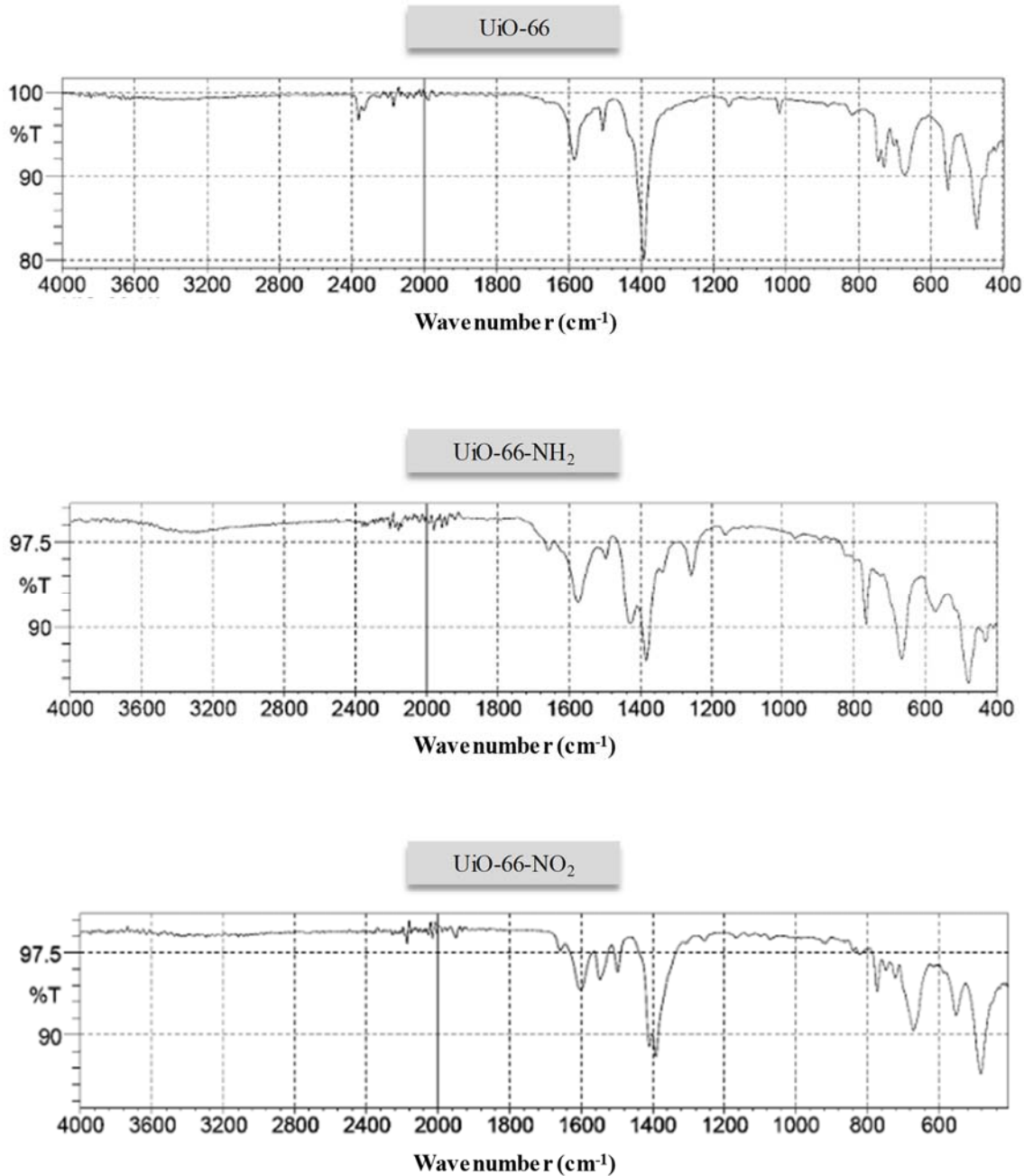


Figure S5. FTIR spectra of synthesized MOFs.

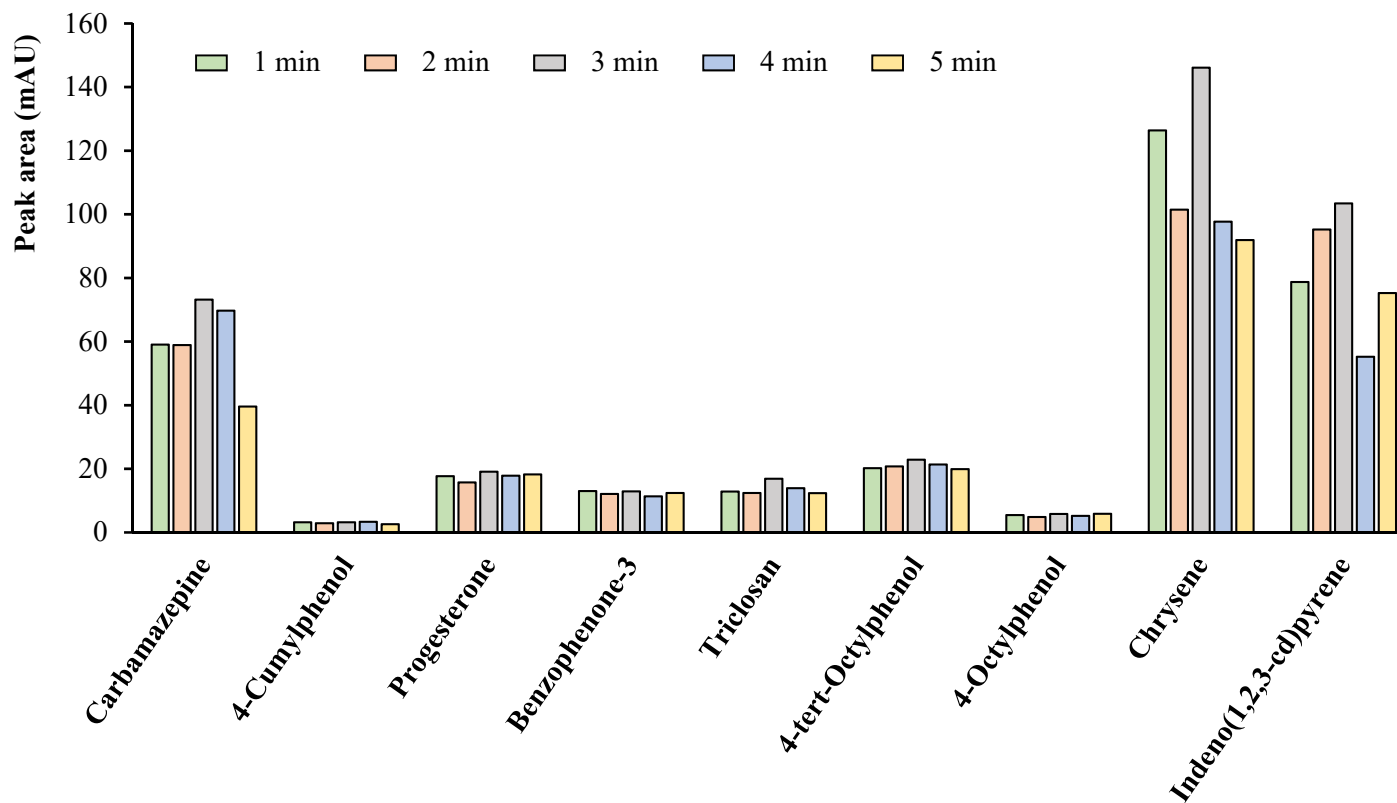


Figure S6. Influence of the extraction time (stirring with vortex) in the extraction efficiency for all analytes in the D- μ SPE-HPLC-DAD method. Fixed conditions as described in the text.

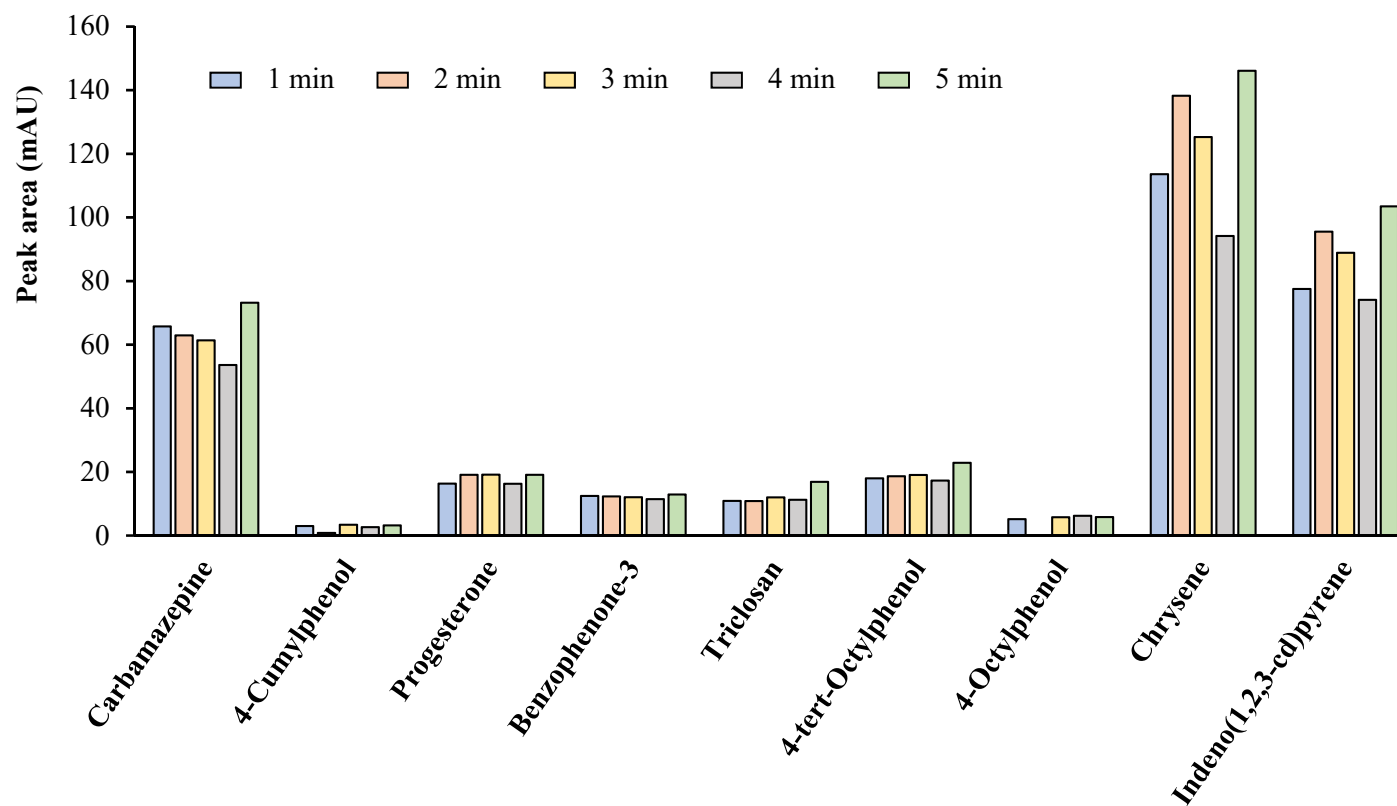


Figure S7. Influence of the elution time (agitation by vortex) in the extraction efficiency of the D- μ SPE-HPLC-DAD method. Fixed conditions as described in the text.

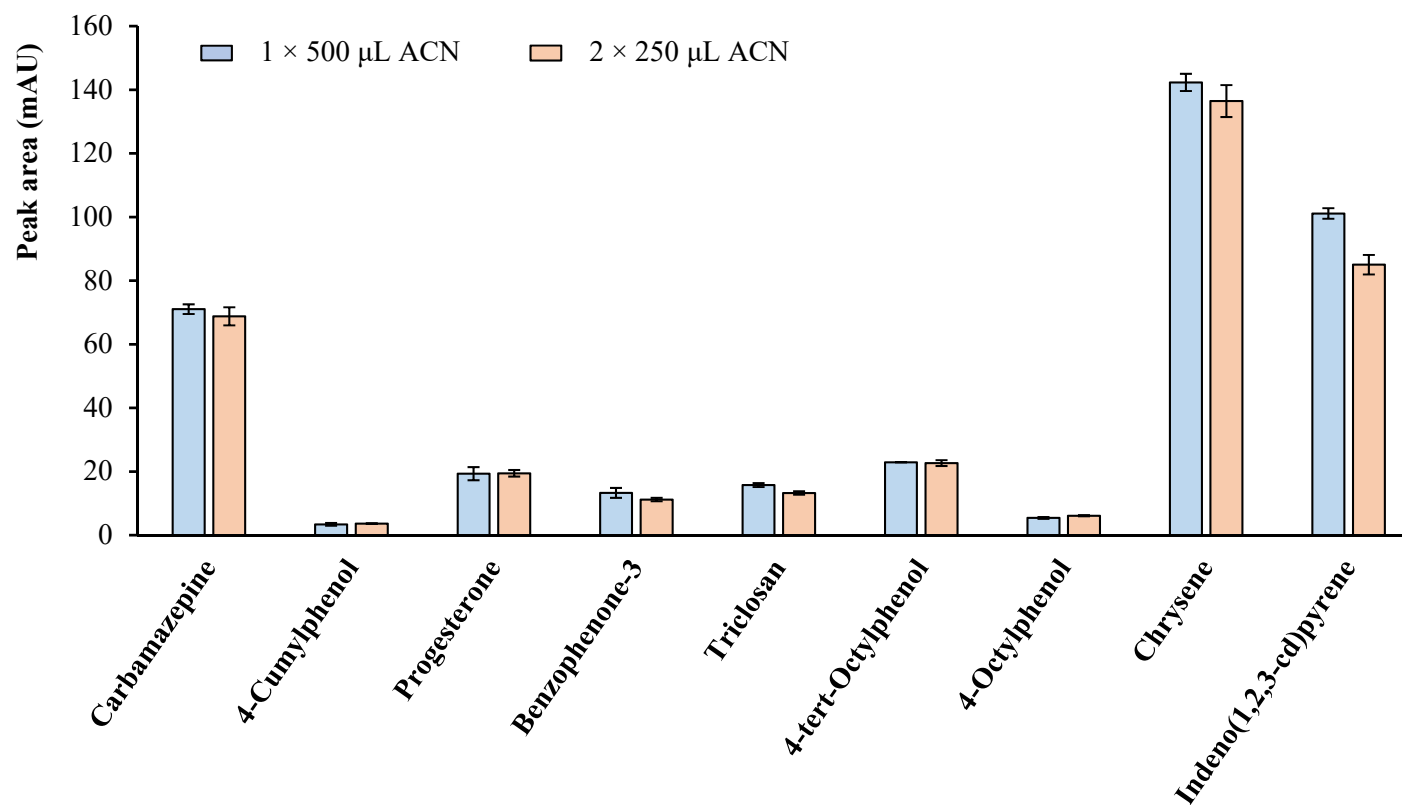


Figure S8. Influence of the number of elution steps in the D- μ SPE-HPLC-DAD method using UiO-66-NO₂ as sorbent. Fixed conditions as described in the text. Experiments were carried out in triplicate.

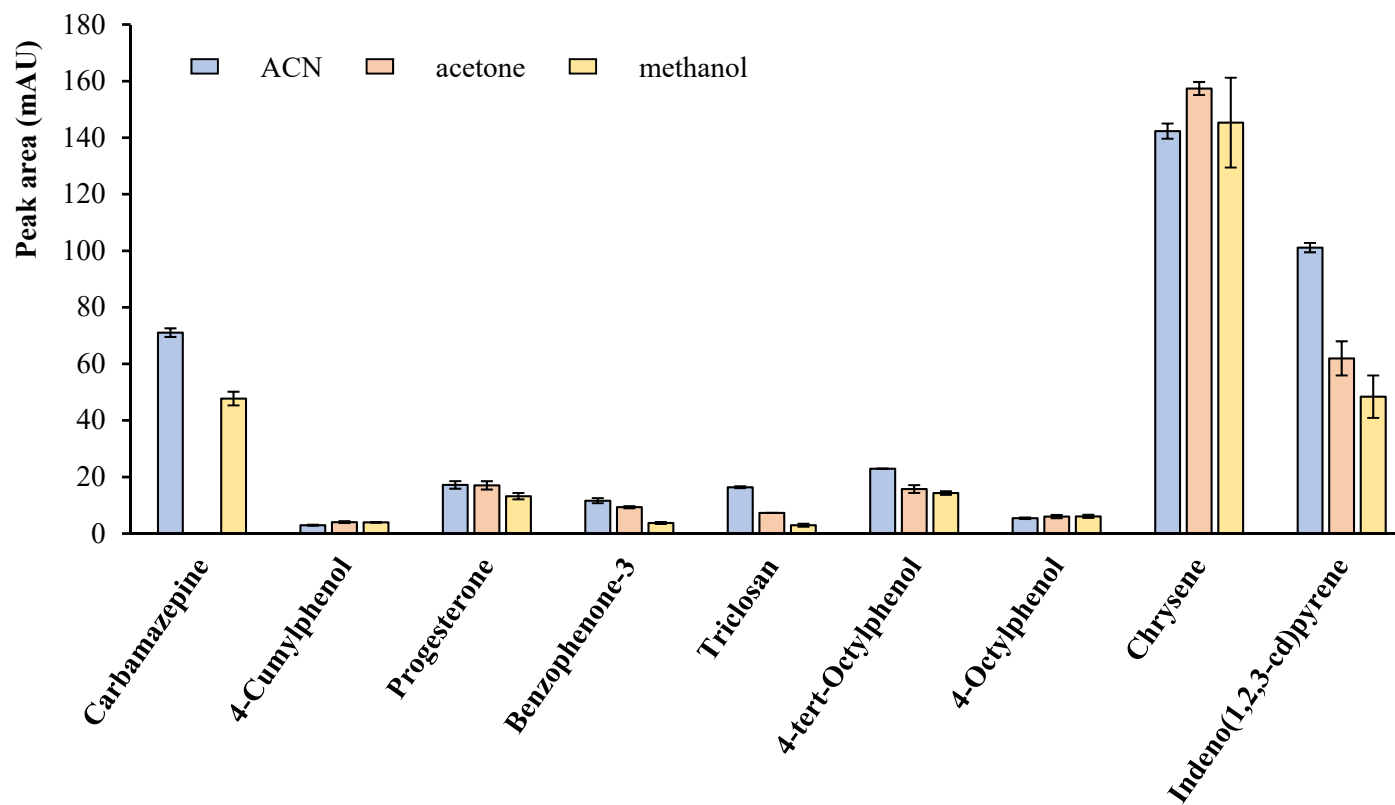
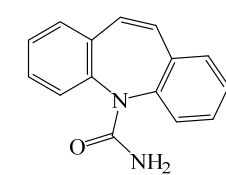
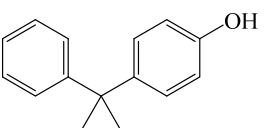
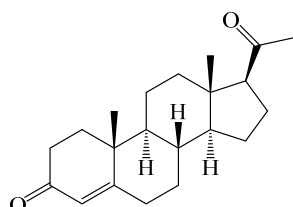
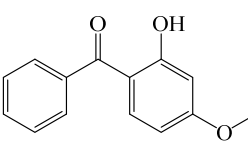
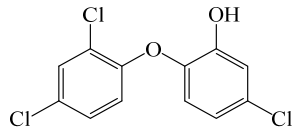
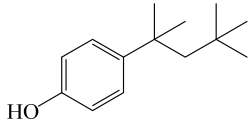
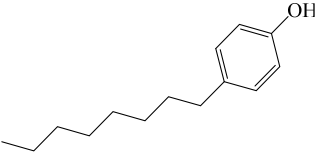
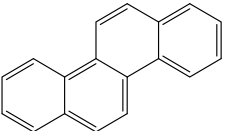
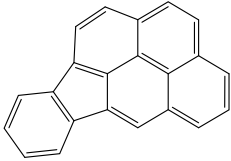


Figure S9. Effect of the nature of the elution solvent in the elution step of the D- μ SPE-HPLC-DAD method using UiO-66-NO₂ as sorbent. Fixed conditions as described in the text. Experiments were carried out in triplicate.

Table S1. Structures and several physicochemical properties of the analytes studied.

Analyte (abbreviation)	Structure	Molecular weight ^a (g·mol ⁻¹)	pK _a ^a	Vapor pressure at 25 °C ^a (atm)	Log K _{ow} ^{a,b}
Carbamazepine (Cbz)		236.27	13.9	$7.61 \cdot 10^{-10}$	1.90
4-Cumylphenol (CuP)		212.29	10.6	$6.55 \cdot 10^{-8}$	4.24
Progesterone (Pg)		314.46	-	$4.53 \cdot 10^{-11}$	3.83
Benzophenone-3 (BP-3)		228.24	7.6	$6.92 \cdot 10^{-9}$	4.00
Triclosan (Tr)		289.54	7.8	$4.29 \cdot 10^{-8}$	5.34

Analyte (abbreviation)	Structure	Molecular weight ^a (g·mol ⁻¹)	pK _a ^a	Vapor pressure at 25 °C ^a (atm)	Log K _{ow} ^{a,b}
4- <i>tert</i> -Octylphenol (<i>t</i> -OP)		206.32	10.2	2.61·10 ⁻⁶	5.18
4-Octylphenol (OP)		206.32	10.2	3.29·10 ⁻⁷	5.63
Chrysene (Chy)		228.29	-	1.12·10 ⁻¹⁰	5.73
Indeno(1,2,3-cd)pyrene (Ind)		276.33	-	2.05·10 ⁻¹²	6.65

^a SciFinder[®] 2018 database

^b *n*-octanol/water partition coefficient

Table S2. Several quality analytical parameters of the HPLC-DAD method.

Analyte	R ^a	s _{y/x} ^b	Slope ± SD ^c	LOD ^d (µg·L ⁻¹)	LOQ ^e (µg·L ⁻¹)	Calibration range (µg·L ⁻¹)
Carbamazepine	0.9990	0.80	0.43 ± 0.03	0.50	1.67	2.00 – 100
4-Cumylphenol	0.9992	0.15	0.09 ± 0.01	1.00	3.33	5.00 – 100
Progesterone	0.9990	0.65	0.33 ± 0.02	0.08	0.25	0.30 – 100
Benzophenone-3	0.9992	0.56	0.33 ± 0.01	0.09	0.30	0.50 – 100
Triclosan	0.9983	0.25	0.10 ± 0.01	0.09	0.30	5.00 – 100
4- <i>tert</i> -Octylphenol	0.9993	0.15	0.101 ± 0.004	0.50	1.67	5.00 – 100
4-Octylphenol	0.9993	0.12	0.082 ± 0.003	0.50	1.67	3.00 – 100
Chrysene	0.9998	1.9	2.66 ± 0.04	0.02	0.07	0.10 – 100
Indeno(1,2,3- <i>cd</i>)pyrene	0.9997	1.1	1.07 ± 0.02	0.03	0.09	0.10 – 100

^a correlation coefficient^b standard deviation of residuals^c confidence intervals for the slope (n = 7) with a signification level of 95%^d limit of detection^e limit of quantification

Table S3. Intra-day precision study of the HPLC-DAD method.

Analyte	Level 1: 6.0 $\mu\text{g}\cdot\text{L}^{-1}$	Level 2: 30 $\mu\text{g}\cdot\text{L}^{-1}$	Level 3: 70 $\mu\text{g}\cdot\text{L}^{-1}$	RSD (%) retention time ^b	Average retention time (min)
	RSD (%) intra-day ^a	RSD (%) intra-day ^a	RSD (%) intra-day ^a		
Carbamazepine	1.2	2.4	2.2	0.21	1.96
4-Cumylphenol	2.7	2.2	2.2	0.13	6.09
Progesterone	0.9	1.8	1.5	0.12	6.40
Benzophenone-3	2.6	1.3	0.7	0.12	6.62
Triclosan	3.1	3.5	0.9	0.07	7.23
4- <i>tert</i> -Octylphenol	3.7	1.5	2.5	0.06	7.63
4-Octylphenol	3.4	2.2	2.9	0.04	9.02
Chrysene	2.3	3.1	1.3	0.08	10.2
Indeno(1,2,3- <i>cd</i>)pyrene	2.8	3.6	1.9	0.12	12.9

^a relative standard deviation of the calculated concentration using the HPLC-DAD calibration curve (n = 5)^b relative standard deviation of the retention times (n = 15)

Table S4. Extraction methods described in the literature for the determination of several of the studied pollutants using solid-based extraction methods and HPLC with UV or DAD detection (to have comparable systems with that of the current study).

Analyte family (number)	Sample prep.	Detector	Sorbent (mg)	Sample (mL)	ER ^a (%) / spiked level	LOD ^b (µg·L ⁻¹)	RSD ^c (%)	Ref.
PAHs ^d (4)	D-µSPE ^e	DAD ^f	MNPs ^g -nylon-6 composite (40)	water (25)	79.4 / 20 µg·L ⁻¹	0.31	4.2	<i>J. Chromatogr. A</i> 2014 , 1345, 43–49
Benzophenones (3)	D-µSPE ^e	DAD ^f	MIL-101(Cr) (12)	toner (20)	-	0.9	<7.4	<i>Talanta</i> 2015 , 132, 713–718
Drugs (3)	D-µSPE ^e	DAD ^f	Fe ₃ O ₄ @polyDA-MWCNTs ^h (15)	plasma (5), CSF ⁱ (5)	86.5–95.1 / 50–200 µg·L ⁻¹	0.4–1.9	<6.4	<i>Anal. Bioanal. Chem.</i> 2018 , 410, 3779–3788
Steroids (3)	MSPE ^j	UV ^k	Fe/CNTs ^l -SrTiO ₃ (20)	milk (20)	-	0.033	2.31	<i>Food Anal. Meth.</i> 2018 , 11, 3179–3189
Cbz, Pg, Tr (6)	D-µSPE ^e	DAD ^f	MIL-53(Al) (5)	water (10)	32.7 – 61.7 2–8 µg·L ⁻¹	0.04–0.15	<8.3	<i>Talanta</i> 2018 , 179, 775–783
Phenols (4)	D-SPE ^m	UV ^k	Fe ₃ O ₄ -OA/CQDs ⁿ (-)	water (20), milk (20)	-	0.09–0.17	<2.8	<i>J. Mol. Liq.</i> 2018 , 261, 155–161
PPCPs ^o (3)	MSPE ^j	UV ^k	Fe ₃ O ₄ /GO ^p (20)	water (50)	-	0.63	4.18	<i>Water Sci. Technol.</i> 2018 , 77, 2220–2227

^a extraction efficiency

^b limit of detection

^c relative standard deviation

^d polycyclic aromatic hydrocarbons

^e dispersive micro-solid phase extraction

^f diode array detection

^g magnetic nanoparticles

^h multi-walled carbon nanotubes

ⁱ cerebral spinal fluid

^j magnetic solid-phase extraction

^k ultraviolet-visible detection

^l carbon nanotubes

^m dispersive solid phase extraction

ⁿ carbon quantum dots

^o pharmaceutical & personal care products

^p graphene oxide

Table S5. Analytical performance of the entire D- μ SPE-HPLC-DAD method in terms of relative recovery, extraction efficiency, and inter-day precision with tap water and wastewater samples.

Analyte	Tap water	Wastewater-1	Wastewater-2	Wastewater-1 (spiked level: 1.5 $\mu\text{g}\cdot\text{L}^{-1}$)		
				E_R^a (%)	RR^b (%)	RSD^c (%)
Carbamazepine	nd	nd	nd	1.15	52.5	13
4-Cumylphenol	nd	nd	nd	36.8	130	17
Progesterone	nd	nd	nd	5.76	17.6	2.8
Benzophenone-3	nd	nd	nd	36.7	133	1.8
Triclosan	nd	nd	nd	92.2	195	4.5
4- <i>tert</i> -Octylphenol	nd	nd	nd	5.99	5.04	5.5
4-Octylphenol	nd	nd	nd	15.3	25.8	3.1
Chrysene	nd	nd	nd	14.6	38.9	5.5
Indeno(1,2,3- <i>cd</i>)pyrene	nd	nd	nd	9.92	34.1	2.8

nd: non-detected

^a extraction efficiency calculated considering the preconcentration achieved with the microextraction method

^b relative recovery (calculated with calibration curves in ultrapure water)

^c relative standard deviation (n = 3, intra-day)