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A NEW STRATEGY FOR PENTACHLOROPHENOL MONITORING IN WATER SAMPLES USING ULTRA-HIGH PERFORMANCE LIQUID CHROMATOGRAPHY - MASS SPECTROMETRY TANDEM

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Abstract

A novel sensitive and rapid analytical approach based on ultra-high performance liquid chromatography - mass spectrometry (UHPLC/MS/MS) tandem was developed for the monitoring of pentachlorophenol in water samples. Chromatographic separation was carried out on Acquity BEH C18 (100 x 2.1 mm, 1.7 µm) column under gradient mode using a mobile phase consisting of acetonitrile/ultrapure water/formic acid. Quantification of pentachlorophenol was performed on a triple-quadrupole tandem mass spectrometer under multiple reaction monitoring (MRM) mode, via a negative electrospray ionization (ESI^-). The limit of quantification of the developed instrumental method was 0.3 µg L^{-1}. The linearity was validated within the concentration range 0.1-100 µg $L^{-1}$with a correlation coefficient (R^2) of 0.998. Intra-day and inter-day precision values were 99.78 and 99.12%, respectively. Moreover, for the application to real water samples, a solid phase extraction method (SPE) was proposed for the extraction and preconcentration of analyte. Some of the main factors involved in the SPE extraction process such solid phase material, elution solvent and sample volume were investigated and optimized in order to maximize the extraction efficiencies. Oasis HLB cartridges showed the best results in term of extraction recovery. High analyte recoveries (between 98.2% and 100.18%) were achieved with the proposed SPE procedure and the extraction RSD was less than 3.1%. In addition, the whole new analytical strategy (SPE-UHPLC/MS/MS) was then successfully applied for pentachlorophenol quantification in natural waters at low part per trillion levels.

Key words: pentachlorophenol, solid phase extraction, tandem mass spectrometry, ultra-high performance liquid chromatography, water analysis

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1. Introduction

Phenols and their derivative compounds commonly exist in the environment due to various industrial activities. Among the hazardous compounds included in the family of chlorophenols, pentachlorophenol (PCP) is considered as the most toxic and was identified as environmental endocrine disruptor (EED) (Yang et al., 2005). Some studies revealed potential possibility to cause decreases in thyroid hormone levels of neonates, neurological disorders, immunodeficiency, or acute pancreatitis (Dallaire et al., 2009; Yang et al., 2006). This organic molecule has been widely used as wood preservative

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in industry, as broad spectrum herbicide and germicide in agriculture and as an intermediate in pharmaceuticals. Moreover, this compound can be formed from phenols during the drinking water disinfection with chlorine affecting the taste and odor of distributed water (Kadmi et al., 2015). All these applications often lead to wastewater, groundwater and even to drinking water contamination.

During the last decades, PCP has drawn a significant scientific attention, due to its high toxicity, hydrophobicity and long environmental persistence related to its stable aromatic ring system and high chloride content (Dudal et al., 2004; Ge et al., 2007; Zheng et al., 2012). The reported toxic effects on human health are related to its estrogenic, mutagenic and carcinogenic properties (Gavrilescu, 2009; Michalowicz and Duda, 2007). The International Agency for Research on Cancer (IARC) classified PCP as group 2B carcinogen (IARC, 1991), possibly carcinogenic to humans. Based on its toxicity and widespread distribution in the environment PCP has been included in both U.S. Environmental Protection Agency and European Union List of priority pollutants and strict restrictions on the maximum admissible concentrations (MAC) in drinking water have been fixed (0.5 μg L^{-1} for total phenols and 0.1 μg L^{-1} for individual compounds) (EPA, 2004; Jakab et al., 2013; Jakab et al., 2014; Wennrich et al., 2000). The MAC value for PCP in inland and other surface waters the set to 1 μg L^{-1}.

Generally, the concentration of PCP is very variable and depends on the type of water. For example, higher levels (in the μg L^{-1} range) were found in landfill leaches (Ho et al., 2008; Wei and Jen, 2002). However, lower levels (in the ng L^{-1} range) have been reported in China's rivers by Gao et al. (2008). Hence, it is of great interest in the environmental field to develop fast and sensitive analytical methods for the monitoring of trace and ultra-trace levels of PCP in water samples. The major challenge in the analysis of such molecule is to attain the high sensitivity required for determination of trace levels in environmental samples.

Over the last decade, a variety of analytical methods including liquid chromatography (LC), gas chromatography (GC), high performance liquid chromatography (HPLC) and thin layer chromatography (TLC) in combination with selective detectors such as electron capture, diode array, mass spectrometer and flame ionization have developed for detection and quantification of PCP and congeners in different samples (Barták et al., 2000; Callejon et al., 2007; Favaro et al., 2008; Gremaud and Tureski, 1997; Pugliese et al., 2004). Among these methods, those based on gas chromatography are the most commonly used due to their high sensitivity and good resolution (Bagheri and Sajari, 2001; Padilla-Sánchez et al., 2011). Additionally, for the GC and GC/MS determinations a derivatisation step (by methylation, pentafluorobenzylation or acetylation) is generally needed to improve the signal detection and peak resolution (Korenman et al., 2003; Llompart et al., 2002) requiring additional time consuming steps and the use harmful reactive chemical agents.

All these reasons pointed out, the interest in the development of more environmentally friendly analytical techniques for the detection of this persistent pollutant. Recently, ultra-high performance liquid chromatography combined with triple quadrupole tandem mass spectrometry (UHPLC/MS/MS) in multiple reaction monitoring mode (MRM) has become a promising analytical tool in the domain of environmental analysis. Such technique could provide high sensitivity, efficiency and molecular weight data for the analytes identification. In this sense, UHPLC/MS/MS appear as suitable techniques for the analysis traces of PCP in environmental water samples.

Nevertheless, due to the low concentration levels of PCP in environmental matrices sample pretreatment is normally required prior to instrumental analysis in order to isolate, clean-up and preconcentrate the target analyte from the matrix and to obtain the required instrumental detection limits. Several sample-handling techniques such as the conventional liquid-liquid extraction (LLE), solid phase microextraction (SPME) and stir bar sorptive extraction (SBSE) are have been reported for the extraction of chlorophenols (Domeno et al., 2005; Llombart et al., 2002; Llorca-Porcel et al., 2009). However, some of these techniques have limitations because they are time-consuming and require high amount of organic solvents. Solid phase extraction (SPE) is one of the most widely used methods for the sample pretreatment in environmental analysis.

In this study, a new analytical strategy coupling solid phase extraction with ultra high performance liquid chromatography tandem mass spectrometry was developed for the quantification of PCP in water samples at low ng L^{-1} level. This work aims to prove the utility and reliability of such analytical strategy for the monitoring of pentachlorophenol in water samples. Several factors affecting the SPE extraction efficiency were studied and optimized in order to improve the target analyte extraction recovery.

The main advantage of the proposed methodology compared with existing methods from the literature (with or without derivatization) is the substantial improvement of its sensitivity for the detection of PCP. Thus it could be a promising analytical tool for the PCP monitoring in real water samples. To our knowledge, this is the first work reporting the analysis of this hazardous organic compound by SPE-UHPLC/MS/MS.

2. Experimental

2.1. Reagents and samples

2.1.1. Reagents

The target compound studied here is pentachlorophenol, obtained from Sigma Aldrich

GmbH (Steinheim, Germany). All chemicals (reagents and solvents) used in this study were of the highest analytical purity grade. Acetonitrile and formic acid were supplied by J.T. Baker (Deventer, Netherlands). Methanol and dichloromethane were obtained from Fischer Scientific-Bioblock (Illkirch, France). Acetic acid, ethyl acetate, diethyl ether and sodium hydroxide were purchased from Acros Organics (Noisy-le-Grand, France).

2.1.2. Preparation of standard solutions and water samples

A stock standard solution (1000 mg L^{-1}) of pentachlorophenol was prepared by dissolving accurate amount in methanol. The working solutions were freshly prepared by appropriate dilutions (to reach the working concentration range) of the stock standard solution in acetonitrile/ultrapure water (55/45, *v/v*). This composition ensured good stability of the chlorophenols in water samples. The ultrapure water (with a resistivity of 18MΩ and a DOC value less than 0.1 mg L^{-1}) used for the preparation of the samples was obtained with an Elga Option-Q DV-25 water purification system (Antony, France). All solutions were stored in glass bottles in the dark at -20°C. To demonstrate the applicability of the developed method real water samples including river water were used in this work.

The samples were collected in October 2013 and January 2014, from different locations (from Britany region, France). All samples were collected in baked glass 10-L amber bottles with Teflon lined caps to ensure sample integrity, filtered through a 0.45 µm cellulose membrane and then stored in the dark at 4°C until their analysis (within one week of collection).

2.2. Apparatus and analytical conditions

The UHPLC/MS/MS system comprised a Waters® Acquity™ UHPLC H-Class system, coupled to a Waters Quattro Premier™ Triple Quadrupole mass spectrometer (Saint-Quentin en Yvelines, France). The chromatographic system contain a binary pump, an auto-sampler and a thermostated column compartment (Waters, Saint-Quentin en Yvelines, France). Chromatographic conditions that directly affect chromatographic separation such as chromatographic column, elution mode, mobile phase composition and aditives were studied and optimized in this work.

Analyte separation was carried out with a Ethylene Bridged Hybrid (BEH) C18 column (100 x 2.1 mm, 1.7 µm; particles, Waters, Ireland) protected by an in-line filter purchased from Waters (Saint-Quentin en Yvelines, France). The analytical column compartment was maintained at 45°C and the auto-sampler at 5°C. The flow rate was 0.4 mL min^{-1} and the injection volume 5 µL. Mobile phases were acetonirile (A) and ultrapure water (B) containing 0.1% (*v/v*) formic acid (pH 3). Elution was done in gradient mode. Details on the optimized UHPLC/MS/MS conditions are presented in Section 3.1.

2.3. Solid-phase extraction (SPE) conditions

The extraction of PCP from water samples was performed by off-line SPE. Oasis HLB cartridges (6 cc, 200 mg) from Waters (Guyancourt, France) were used for the SPE experiments. A 12-port Visiprep SPE vacuum manifold obtained from Supelco (Bellefonte, PA, USA) was used for sample extraction. Within this study, Oasis HLB (Hydrophilic-Lipophilic Balanced) cartridges (6cc, 200 mg, Waters, Milford, MA) containing a macroporous poly(divinylbenzene-co-N-vinylpyrrolidone) copolymer were selected for the development and optimization of the SPE method. The developed SPE procedure was carried out as follows: Oasis HLB cartridges were conditioned using 2 × 2 mL acetonitrile, and 2 × 2 mL methanol and then equilibrated with 2 × 2 mL of ultrapure water acidified with formic acid (0.1%) at a flow rate of 5 mL min^{-1}. The analyte was spiked into a water sample of 250 mL. The water samples were immediately loaded on the SPE cartridges at 5 ml min^{-1}. After the loading step, the cartridges were cleaned with ultrapure water adjusted to pH 3 with formic acid (2 × 2 mL). The analyte was then eluted successively with 2 × 2 mL of methanol at a flow rate of 3 mL min^{-1}.

The eluates were transferred to a clean conical graduated glass Pyrex® tube (VWR, Fontenay-sous-Bois, France) and concentrated by evaporation under a nitrogen stream to a final volume of 0.1 mL (concentration factor of 2.500). The obtained extracts are then reconstituted using acetonitrile/ultrapure water (55/45, *v/v*) and transferred to injection vials. Finally, the extracts were stored at 4°C until further analysis.

2.4. Quality parameters

2.4.1. Linearity, limit of detection and limit of quantification

The linearity of the method was studied from the calibration curves prepared from spiked ultrapure water samples at seven pentachlorophenol concentrations ranging from 25 to 200 µg L^{-1}. Each solution was analysed in triplicate. The calibration curves were plotted by the peak area versus the concentration of analyte. The linearity was evaluated by linear regression analysis determined by the least squares regression method.

This method was used to determine the slope, intercept, and correlation coefficient (R^2) of the linear regression equation. The instrumental limit of detection (ILD) is the lowest concentration of analyte that gives a measurable response (signal to noise ratio (S/N) of 3), while the instrumental quantification limit (IQL) is the lowest concentration of analyte which can be accurately quantified (S/N of 10).

2.4.2. Precision and accuracy

The precision of the proposed instrumental method was evaluated in terms of repeatability (intra-day and inter-day precision). The repeatability values were expressed as relative standard deviation (RSD, %). It was determined by analyzing six replicates (n=6) of IQL samples. The intra-day precission was assed by analyzing the IQL samples six times within a single day and the inter-day precision was calculated by determining the IQL samples over three days.

2.4.3. Extraction recovery and matrix effect

SPE recoveries were determined quantitatively at low and high concentration levels. The extraction recoveries (R, %) were assessed by comparing the analytical results obtained for an extracted sample using the developed SPE procedure to an unextracted pure standard. Thus, the extraction recovery of pentachlorophenol was calculated as ratio of the peak areas of the extracted and unextracted samples.

The matrix effect (ME = C/D, %) was determined as described previously by Kadmi et al. (2014). It was evaluated by comparing the peak areas obtained from the analyte in the presence of the matrix (C: samples spiked for extraction) to the one in absence of the matrix (D: pure standard solution). In this study, the matrix effect was evaluated by using a real water samples. Then, the relative standard deviations (RSD, %) were also calculated.

3. Results and discussion

3.1. Optimization of UHPLC/MS/MS conditions

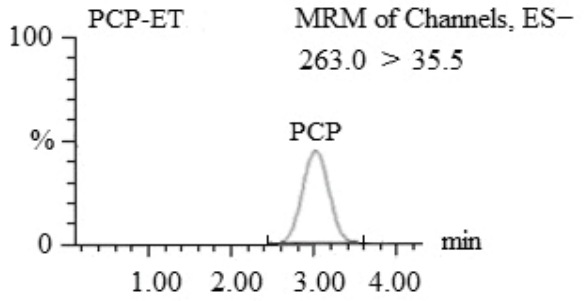
The primary aim of this work was to evaluate the potential of UHPLC system for the analysis of pentachlorophenol in water samples. The UHPLC system takes full advantage of chromatographic separation with high resolution and rapid analysis time by using columns packed with smaller particles (1.7 µm). Chromatographic conditions such as stationary phase, mobile phase composition and pH and elution mode were optimized in this study through several tests in order to obtain a good resolution, increase the signal of PCP in water samples and short run time. Several reversed phase columns such as Acquity BEH HSS T3 (100 x 2.1 mm, 1.7 µm), Acquity BEH C8 (100 x 2.1 mm, 1.7 µm) column and Acquity BEH C18 column (100 x 2.1 mm, 1.7 µm) were carefully tested in order to obtain optimal efficiency, selectivity, symmetric peak shape and reduced retention time. The Acquity BEH C18 (100 x 2.1 mm, 1.7 µm) was finally chosen in this work because it gives good peak shape and sensitivity. Different compositions of binary mixtures (of acetonitrile-ultrapure water and methanol-ultrapure water with different additives such as acetic or formic acid), were investigated as eluting solvents in both isocratic and gradient modes to achieve good separation in minimum run time for the target analyte. It was found that acetonitrile gave the better chromatographic separations (data not shown) under gradient mode. Moreover, it was observed that the addition of formic acid (0.1% *v/v*) remarkably improve the peak symmetry and the ionization of the target molecule (Table 1).

Therefore, a mobile phase of acetonitrile-water with formic acid (0.1%, *v/v*) was selected in this work for PCP separation and quantification. Elution was done in gradient mode performed as folllows: by increasing linearly the content of organic modifier from 5% (initial) to 55% within 2 min, then, the percentage of A was incresed linearly up to 100% between 2-4 min and then return to initial conditions 5% (A) for a 1.5 min (Table 1). Under optimized chromatographic conditions the obtained retention time for PCP was 3 min (Fig. 1). In addition, blanks were periodically run during the analysis to confirm the absence of contamination.

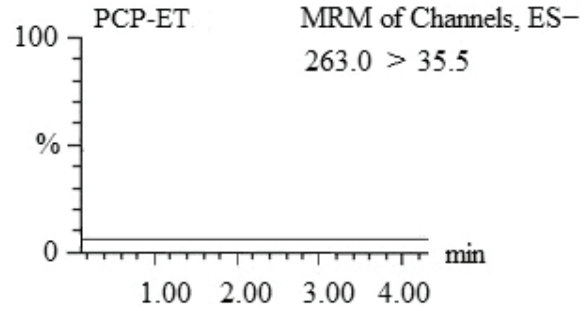
Table 1. Optimized conditions of UHPLC and MS/MS for the pentachlorophenol analysis

UHPLC conditions	
Column	Waters Acquity BEH C18 (100 x 2.1 mm, 1.7 µm)
Column temperature (^oC)	45
Mobile phase	Acetonirile (A) and ultrapure water (B) containing 0.1% (*v/v*) formic acid (pH 3)
Gradient program	5-55% (A) within 0-2 min; 55-100% (A) within 2-4 min; return to the initial conditions of 5% (A) for a 1.5 min
Flow rate of the mobile phase	0.4 mL min^{-1}
Injection volume	5 µL
MS/MS conditions	
Source temperature (^oC)	120
Capillary voltage (kV)	3.0
Desolvation temperature (^oC)	350
Desolvation gas flow (L h^{-1})	750
Cone gas flow (L h^{-1})	75
Quantification transition, m/z	263.0 > 35.5
Confirmation transition, m/z	263.1 > 263.5
Cone voltage (V)	25
Collision energy (eV)	10

Atmospheric pressure chemical ionization (APCI) and ESI (electrospray ionization) interfaces with positive and negative ionization were evaluated in order to get the optimal analytical conditions for the determination of PCP.



(a)



(b)

Fig. 1. Representative MRM chromatogram obtained from UHPLC/MS/MS analysis: (a) ultrapure water sample spiked with a standard solution of pentachlorophenol (concentration level IQL); (b) ultrapure water sample (blank)

Obtained results revealed that the optimal conditions for analyte quantification were achieved with ESI interface functioning in negative mode due to its high sensitivity. The different mass spectrometric parameters of the interface were optimized by direct injection of standard solution of analyte (50 µg L^{-1}) into the mass spectrometer. The selected parameters are as follows: source temperature, 120°C; desolvatation temperature, 350°C and a capillary voltage, 3kV. Nitrogen was used as desolvatation gas (750 L h^{-1}) and as cone gas (75 L h^{-1}).

Optimization of cone voltage was carried out by scanning the voltage from 10 to 120V with the full scan mode and a scan time of 1s. No additional molecular fragment was observed by increasing voltage and finally a cone voltage of 25V was established to be sufficient for analyte detection because this provided very good sensitivity for PCP. The MS/MS parameters selected for the determination of considered molecule were detailed in Table 1. Thus, these parameters remained fixed during a single analysis.

Moreover, in this study, two sensitive MRM transitions were selected for analyte determination. Indeed, two transitions have to be recorded for the considered compound in order to get a sufficient number of identification points for a suitable confirmation. Thus, in this work, the peak area of the most intense transition was used for quantitative purposes and the less intense transition was used for the confirmation of each analyte. The selected multiple reaction monitoring transitions PCP analysis are presented in Table 1.

3.2. Analytical performance of the UHPLC/MS/MS method

Once optimized, the instrumental method was characterized in terms of limit of detection, limit of quantification, precision, accuracy, and extraction recovery. The tests were carried out without organic interfering species (ultrapure water). The obtained results are summarized in Table 2. External calibration curve (6 levels and 1 blank) was established by plotting the peak areas against analyte concentration. Linear range of pentachlorophenol was obtained in the range of 0.1 – 100 µg L^{-1}. The slope and intercept value for calibration curve was y = 409.63x + 85.01. The results show excellent correlation between the peak area and concentration of PCP (R^2= 0.998). As stated previously, the instrumental limits of detection and quantification (IDL and IQL) of the proposed method were calculated based on a signal to noise ratio (S/N) of 3 and 10 respectively.

The instrumental IDL and IQL were found to be 0.1 and 0.3 µg L^{-1}, respectively. The precision of the proposed instrumental method was expressed as intra-day and inter-day relative standard deviations (RSDs). It was assessed by replicate (n=6) analysis of ultrapure water samples spiked with PCP at a concentration level of 10 µg L^{-1}. The obtained intra-day and inter-day RSDs values were 99.78% and 99.12%, respectively. These results highlight the good performance of the new developed instrumental method.

Table 2. Performance data of the optimized instrumental UHPLC/MS/MS method for the analysis of pentachlorophenol in water

Compound	***Value***
Linear range (µg L^{-1})	0.1 - 100
Calibration curve	y = 409.63x + 85.01
Regression coefficient (R^2)	0.998
IDL[a] (µg L^{-1})	0.1
IQL[a] (µg L^{-1})	0.3
Intra-day precision (mean ± RSD[b], µg L^{-1})	99.78
Inter-day precision (mean ± RSD[b], µg L^{-1})	99.12

[a]*Instrumental detection and quantification limit*
[b]*RSD, relative standard deviation expressed in percentage. Calculated for six samples (n=6) spiked at 10 µg L^{-1}*

3.3. Extraction recovery

In order to have a more sensitive method for the quantification of pentachlorophenol in water samples, an extraction-preconcentration step prior to chromatographic analysis is necessary. As stated below, in order to decrease the limit of detection and quantification of PCP in water sample an off-line solid phase extraction methodology was developed in this work. SPE experiments were carried out after the optimization of UHPLC/MS/MS conditions. The optimization of the extraction process was performed in order to attain excellent recoveries for the target compound in a single extraction step. According to literature data, Oasis HLB cartridges are one of the most used, because they are able to retain a large list of organic pollutants (acidic, neutral and basic molecules) through its unique ratio of hydrophilic N-vinylpyrrolodone and lipophilic divinylbenezene sorbent (de Almeida et al., 2000). Thus, Oasis HLB cartridges were selected and used in this work.

The performance of the proposed SPE protocol was investigated through extraction recoveries obtained for six replicates in spiked ultrapure water samples at three quality control concentrations (10, 20 and 100 µg L^{-1}). Examination of results obtained by using the optimized SPE procedure showed very good recoveries for PCP (Table 3). Indeed, the calculated extraction recoveries were within the range of 2.4% and 3.15% at all quality control levels (Table 3).

On the other hand, the instrumental detection limits of the developed method were 0.1 µg L^{-1}; while detection limits obtained with the overall SPE-UHPLC/MS/MS method was 0.04 ng L^{-1}. These results are better than those previously reported in the literature for SPE-LC analysis (Opeolu et al., 2010) and are below the legal tolerance level for each chlorophenol in drinking water (100 ng L^{-1}) according to the European Community Directive (Elci et al., 2011). The proposed SPE-UHPLC-MS/MS method therefore allowed quantification limits in the range of ng L^{-1} and an enrichment factor of 2500 for the both phenolic compounds (sample volume, 250 mL to 0.1 mL).

3.4. Analysis of real water samples

The developed SPE-UHPLC/MS/MS method was then applied for the determination of extraction recoveries from different real water samples (river water) collected from different locations situated in the Britany region (France) in order to test the possible effects of the water matrix constituents and also the applicability of the proposed analytical methodology for environmental use.

The matrix effect is a phenomenon with great influence in liquid chromatography associated to mass spectrometry. Indded, a such phenomenon disturb the ionization of analytes leading generaly to an enhancement or an inhibition of compound signal (Kasprzyk-Horden et al., 2008).

In this study the matrix effects were studied in three surface water samples (used to supply drinking water treatment plant) spiked before extraction with a standard solutions of PCP at two levels of concentration (10 and 50 µg L^{-1}). All experiments were performed in six replicates (n=6). The extraction recoveries obtanied with real water (surface water) samples are summarized in Table 4.

Extraction recoveries obtained with HLB cartriges were between 97.87% and 101.31% with relative standard deviations less than 4.5%. The obtained results are very close with the ones obtained in ultrapure water. Moreover, the signal obtanied by the analysis of extracts at two concentration levels was compared to that obtained with pure standard solutions injected six times onto the chromatographic system.

Table 3. Recovery results and relative standard deviations (RSD, %) obtained with Oasis HLB cartridges after the extraction of 250 mL ultrapure water sample spiked at three concentration levels

Samples	***Sample (A)***	***Sample (B)***	***Sample (C)***
Concentration of blank (µg L^{-1})	n.d.[a]	n.d.[a]	n.d.[a]
Spiked concentration (µg L^{-1})	10	20	100
Founded (µg L^{-1})	0.982	9.979	50.09
Recovery (%)	98.20	99.79	100.18
RSD (%, n=6)	2.8	3.15	2.4

[a]*n.d. referred to not detected.*

Table 4. Recovery study of the developed method for PCP analysis performed using real samples (water river) spiked at two concentrations levels (10 and 50 µg L^{-1})

Real sample	***Conc. spiked (µg L^{-1})***	***Conc. measured (µg L^{-1})***	***Recovery (%)***	***RSD (%, n = 6)***
Water R1	10	9.787	97.87	3.50
	50	49.72	99.44	3.10
Water R2	10	10.13	101.31	4.25
	50	49.84	99.68	3.78
Water R3	10	9.908	99.08	3.63
	50	49.11	98.22	4.39

Under these conditions no suppression or enhancement of the analyte signal was observed. Thus, no detectable matrix effect was observed. These results clearly demonstrate that the developed SPE-UHPLC/MS/MS methodology is not influenced by the water quality and the extraction recoveries obtained in ultrapurewater are transposable to real water samples. Therefore, the proposed analytical strategy is feasible to be used for the PCP monitoring at ultra trace levels in environmental water samples.

5. Conclusions

A new highly sensitive UHPLC/MS/MS method for the determination of ultra-trace levels of PCP in water samples was developed in this study. Good linearity, precision, accuracy, lower limits of detection, and limits of quantification were obtained. The proposed SPE methodology led to satisfactory extraction recoveries and high pre-concentration factors of the considered target analyte in different environmental water samples. In addition, in the described conditions, no significant matrix effect influences the PCP quantification under real analysis conditions.

To the best of our knowledge this is the first analytical strategy allowing highly sensitive quantification of this hazardous organic compound in environmental water samples.

In conclusion, this simple, rapid, low-cost, and reliable method can be applied for routine quantitative analysis of the target analytes at ultra-trace concentration levels (ng L^{-1}) in different types of water samples. This method can be a useful analytical tool for future toxicological and water quality surveillance studies or for the evaluation of the water disinfection processes.

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