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PAPER IN FOREFRONT

Salting-out-enhanced ionic liquid microextraction with a dual-role solvent for simultaneous determination of trace pollutants with a wide polarity range in aqueous samples

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Abstract In real aquatic environments, many occupational pollutants with a wide range of polarities coexist at nanogram to milligram per liter levels. Most reported microextraction methods focus on extracting compounds with similar properties (e.g., polarity or specific functional groups). Herein, we developed a salting-out-enhanced ionic liquid microextraction based on a dual-role solvent (SILM-DS) for simultaneous detection of tetracycline, doxycycline, bisphenol A, triclosan, and methyltriclosan, with log K_{ow} ranging from −1.32 to 5.40 in complex milk and environmental water matrices. The disperser in the ionic-liquid-based dispersive liquid–liquid microextraction was converted to the extraction solvent in the subsequent salting-out-assisted microextraction procedures, and thus a single solvent performed a dual role as both extractant and disperser in the SILM-DS process. Acetonitrile was selected as the dual-role solvent because of its strong affinity for both ionic liquids and water, as well as the extractant in the salting-out step. Optimized experimental conditions were 115 μL [C_8MIM][PF_6] as extractor, 1200 μL acetonitrile as dual-role solvent, pH 2.0, 5.0 min ultrasound extraction time, 3.0 g Na_2SO_4, and 3.0 min vortex extraction time. Under optimized conditions, the recoveries of the five pollutants ranged from 74.5 to 106.9%, and their LODs were 0.12–0.75 μg kg^{-1} in milk samples and 0.11–0.79 μg L^{-1} in environmental waters. Experimental precision based on relative standard deviation was 1.4–6.4% for intraday and 2.3–6.5% for interday analyses. Compared with previous methods, the prominent advantages of the newly developed method are simultaneous determination of pollutants with a wide range of polarities and a substantially reduced workload for ordinary environmental monitoring and food tests. Therefore, the new method has great application potential for simultaneous determination of trace pollutants with strongly contrasting polarities in several analytical fields.

Keywords Simultaneous quantification of pollutants with contrasting polarity · Salting-out-enhanced ionic liquid microextraction · Dual-role solvent · Antibiotic detection · Aqueous samples

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Introduction

Tetracyclines (TCs) are antimicrobial agents widely used for therapeutic purposes as well as for prevention and treatment of infection, growth promotion, and production efficiency [1]. To control exposure to TCs and ensure milk quality, a regulatory maximum residue limit (MRL) of 0.1 mg kg^{-1} in milk was established by the European Union (EU), Food and Agriculture Organization of the United Nations/World Health Organization (FAO/WHO), and US Food and Drug Administration (FDA) [2]. TCs are highly polar pollutants with tetracycline (TCL; log K_{ow} = −1.32 [3]) and doxycycline

(DOX; log K_{ow} = −0.02 [4]) being the two most prevalent pollutants. Bisphenol A (BPA; log K_{ow} = 3.32) and triclosan (TCS; log K_{ow} = 4.76) are known endocrine-disrupting chemicals with moderate polarity [5, 6]. They are widely used in industrial and consumer products and are known to cause abnormalities in invertebrate, fish, avian, reptilian, and mammalian species. They are further used as base chemicals in the manufacture of polycarbonate plastics and the resin lining of food and beverage containers resulting; these uses eventually lead to exposure in humans [7]. Human exposure to BPA may elevate the risk of obesity, diabetes, and coronary heart disease, and exposure in aquatic organisms can affect entire aquatic ecosystems [8]. TCS is well known for its use in antimicrobial and preservative agents in many typical household and personal care products, such as shampoo, liquid soap, and toothpaste [9]. Widespread use of TCS has led to its presence at relatively high concentrations (1–50 μg L^{-1}) in many environmental matrices [10, 11]. TCS can be degraded by exposure to UV radiation to chlorophenols and dioxin, or by microorganisms to methyltriclosan (MTCS) [12]. Both TCS and MTCS bioaccumulate in lipid tissues with a bioaccumulation factor of 2000–8700 [13]. MTCS is more lipophilic (log K_{ow} = 5.4) and persistent than its parent compound (log K_{ow} = 4.8) [14]. Human exposure to TCS (or MTCS)-contaminated foods can lead to conformation changes in human serum albumin (HSA) through formation of a TCS (or MTCS)–HSA complex and altering of protein function in humans [15].

Different contaminants with highly contrasting polarities are often present in food and environmental matrices. Because of the affinity between target analytes and extraction solvent, a single pretreatment method can only extract compounds with similar properties (e.g., polarity or specific functional groups) [16]. There is a paucity of information concerning pretreatment methods that can be used for simultaneous extraction of pollutants with a wide range of polarities. Development of a single pretreatment method to simultaneously extract pollutants with contrasting polarities from food and environmental matrices would greatly reduce the workload and cost of analytical tests.

In recent years, several novel liquid-phase microextraction (LPME) methods were developed to address the limitations of traditional extraction methods such as requiring large amounts of organic solvent, time-consuming operation, environmentally harmful reagents, and human-health hazards [17]. These LPME methods include hollow fiber LPME [18], ionic liquid dispersive LPME [19], effervescence-assisted switchable solvent-based microextraction [20], "no-organic solvent microextraction" [21], and so on. LPME microextraction procedures have received considerable attention because they require microliter-level extractant and disperser volumes, reduce processing time, and are relatively environmentally benign. Since the target analytes are transferred to the extractant in the microextraction process according to the principle of "like-dissolves-like", extraction recoveries are generally high only for weakly polar compounds such as polybrominated diphenyl ethers (log K_{ow} ≈ 8–12) [22], pesticides, polychlorinated biphenyls, and polyaromatic hydrocarbons (log K_{ow} ≈ 3–7) [23]. In contrast, single-step LPME methods achieved only low extraction recoveries (ca. 28.7–41.3%) for highly polar compounds (log K_{ow} < 0) when water-immiscible organic solvents or alkylimidazolium ionic liquids were used as the extractant [24].

To satisfy the technical requirements of simultaneous determination of coexisting environmental pollutants with widely contrasting polarities, we developed a novel LPME method called salting-out-enhanced ionic liquid microextraction based on a dual-role solvent (SILM-DS). The method can be used for simultaneous quantification of TCL, DOX, BPA, TCS, and MTCS residues with log K_{ow} values ranging from −1.32 to 5.40 in complex milk and environmental water matrices. The technique integrates the advantages of IL-based dispersive liquid–liquid microextraction (IDLM) with salting-out-assisted microextraction (SAME) to achieve higher extraction efficiencies for pharmaceutical and phenolic pollutants with wide-ranging polarities. The disperser in the IDLM was converted to the extractant in the subsequent SAME procedure, and thus a single solvent performed dual roles as both extractant and disperser in a SILM-DS process. To the best of our knowledge, this is the first microextraction method developed for simultaneous quantification of coexisting pharmaceutical and phenolic pollutants covering a wide range of polarities in food and environmental matrices. The newly developed method greatly reduces the analytical workload for ordinary environmental monitoring and food tests, and thus has great application potential in several analytical fields. Moreover, dual usage of a kind of organic solvent cleverly decreased its consumption, which results a more environmentally friendly method, and it also provides high extraction efficiency, simplicity, low cost, and comparable method quantification limits (MQLs).

Experimental

Reagents and chemicals

Certified reference standards (purities >98%; TCL, DOX, BPA, TCS, and MTCS) were obtained from Sigma-Aldrich (St. Louis, MO, USA); their chemical structures are shown in Fig. 1. Chromatography-grade methanol and acetonitrile were purchased from Merck (Darmstadt, Germany). The following ionic liquids (ILs) were all obtained from Shanghai Chengjie Chemical Co. (Shanghai, China) with purities >99.0%: 1-butyl-3-methylimidazolium hexafluorophosphate ($[C_4MIM][PF_6]$), 1-hexyl-3-methylimidazolium hexafluorophosphate ($[C_6MIM][PF_6]$), and 1-octyl-3-methylimidazolium hexafluorophosphate ($[C_8MIM][PF_6]$). Salts used in the procedure were obtained from Aladdin

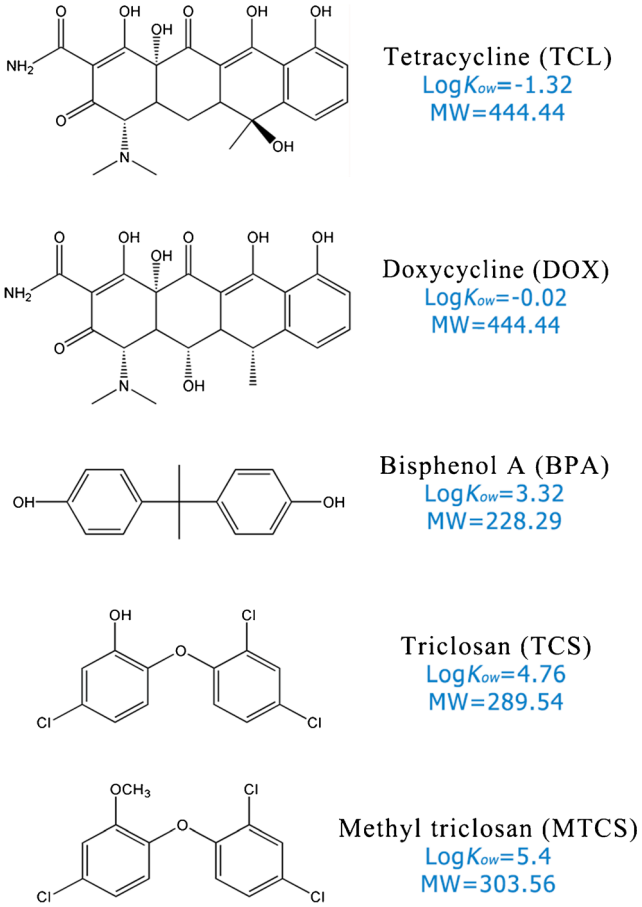


Fig. 1 Basic information for the five analytes studied

Industrial Co. (Shanghai, China) and had purities >99%. Millipore-Q ultrapure water (18.2 MΩ cm, 25 °C) was used for preparation of the mobile phase and sample solutions (Millipore, Billerica, MA, USA). A mixed stock solution (20 mg L^{-1}) was prepared in methanol and stored at 4 °C. Three types of bovine milk, namely nonfat milk (without fat), low-fat milk (2% fat content), and whole milk (6% fat content) were produced by Yili Milk Company (Yili, China). Wenruitang River (WRTR) water samples were collected from urban rivers in Wenzhou, China. Sea water was obtained from a coastal area near Yantai, China, and tap water was taken directly from our laboratory in Wenzhou, China.

Instrumentation

An Agilent 1260 HPLC system (Agilent, Santa Clara, CA, USA), equipped with a UV detector and a Zorbax Eclipse SB-C_{18} column (4.6 mm × 150 mm, 5 μm particle diameter), was used for separation of target analytes with a wide range of polarities. Manual injection was performed using a microsyringe and 20.0-μL sample loop. Solutions were stirred with an HJ-6A magnetic heater-stirrer with an 8 mm × 4 mm stir bar (Jiangsu Jintan Medical Instrument Factory, Jintan, China). A KQ-300VDE ultrasonic cleaner was used at a frequency and output power of 45 kHz and 300 W, respectively (Kunshan Ultrasonic Instrument Co., Kunshan, China). Samples were mixed with an XH-D vortex mixer (Shanghai Zhengqiao Instrument Co., Shanghai, China).

Preparation of bovine milk and environmental water samples

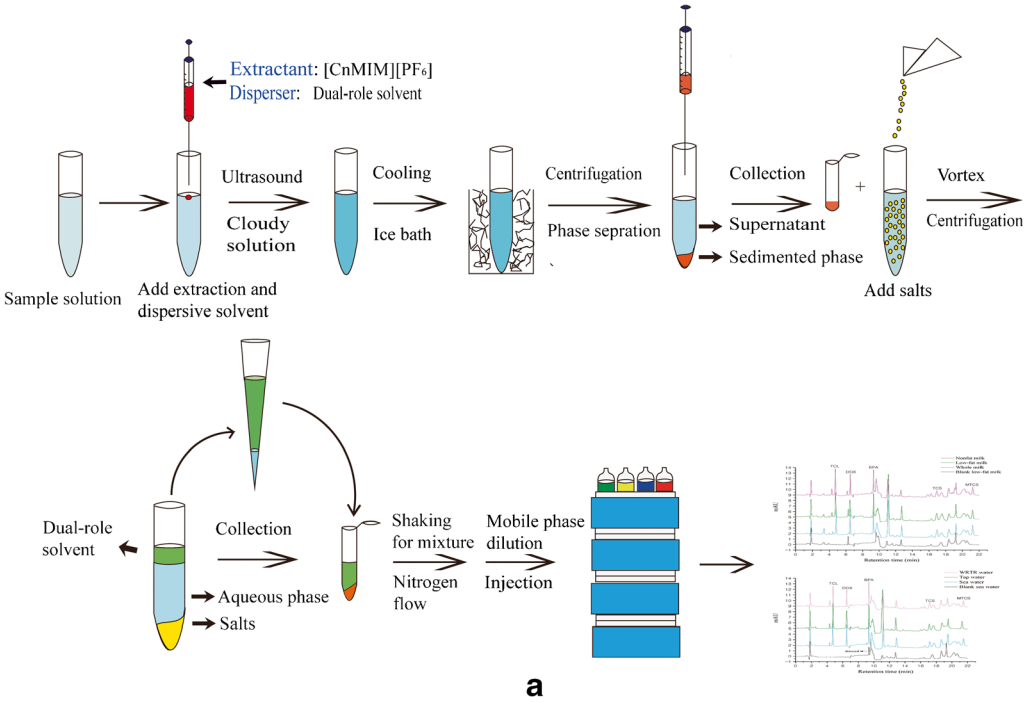
An appropriate amount of stock solution was added to the bovine milk and environmental samples to prepare test samples at the microgram per liter level. Aliquots of milk (3 mL), including the blank and spiked samples, were introduced into a 15-mL centrifuge tube, followed by addition of 3.0 mL water. The sample was ultrasonically shaken for 1 min and stored in a refrigerator at 4 °C for 15 min. Finally, the sample was centrifuged for 15 min at 3000 rpm and filtered with a 0.22-μm PTFE membrane filter to remove any denatured proteins. The resulting solution was referred to as the pretreated milk sample in subsequent microextraction procedures. Three environmental waters, namely WRTR, tap, and sea water, were filtered with a 0.22-μm PTFE membrane, and the resulting solutions were referred to as the pretreated water samples.

HPLC–UV conditions

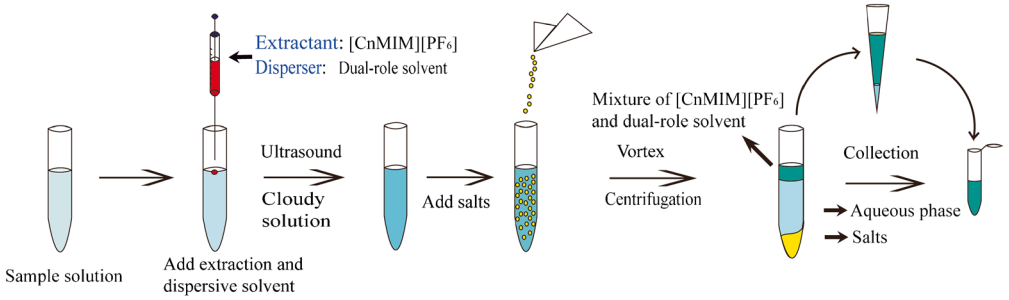
The mobile phase consisted of acetonitrile (A), 0.01 mol L^{-1} Na_2HPO_4 aqueous solution (pH 2.5) (B), and water (C). The gradient program for the mobile phase was 0–5 min, 15–32% A and 85–68% B; 5–8.5 min, 40% A and 60% C; 8.5–10 min, 40–60% A and 60–40% C; 10–17 min, 60% A and 40% C; and 17–22 min, 75% A and 25% C. The flow rate was 1.0 mL min^{-1} for 0–5 min followed by 1.5 mL min^{-1} for 5–22 min. The column temperature was set at 30 °C at the beginning, 25 °C at 6 min, and 15°C at 12 min. The detector wavelength was initially set to 355 nm and then changed to 278 nm at 7 min.

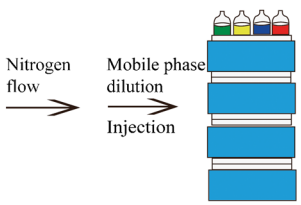
SILM-DS procedure

A schematic of the integrated SILM-DS procedure is shown in Fig. 2a. A 5-mL sample of pretreated milk or environmental water was placed in a 15-mL screwcap glass conical centrifuge tube. For the first step of the microextraction, ionic liquid [C_nMIM]PF_6 (70–145 μL) and water-miscible disperser (800–1800 μL) were added to the samples. Following ultrasonic mixing for 1.0–9.0 min, a cloudy solution formed. After centrifugation, the IL extraction solvent was sedimented at the bottom of the conical tube and then transferred to another tube. For the second step of the microextraction, 1.5–4.5 g salt was added to the remaining aqueous solution containing dispersive solvent

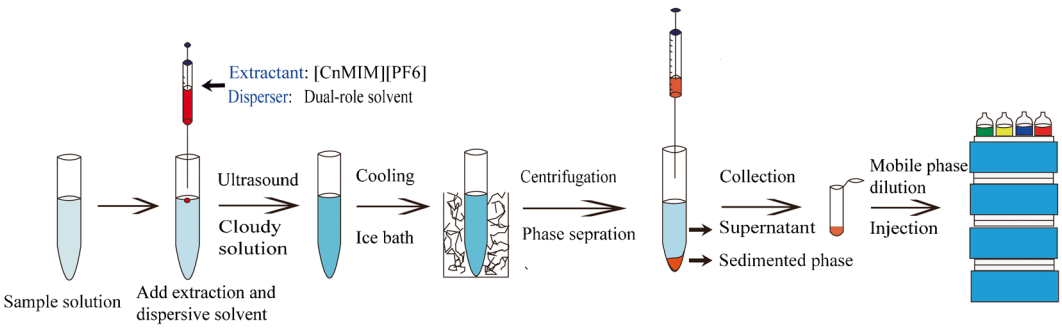

Extractant: [CnMIM][PF6]
Disperser: Dual-role solvent
Sample solution
Add extraction and dispersive solvent
Ultrasound
Cloudy solution
Cooling
Ice bath
Centrifugation
Phase sepration
Collection
Supernatant
Sedimented phase
Add salts
Vortex
Centrifugation
Dual-role solvent
Collection
Aqueous phase
Salts
Shaking for mixture
Nitrogen flow
Mobile phase dilution
Injection

a


Extractant: [CnMIM][PF6]
Disperser: Dual-role solvent
Sample solution
Add extraction and dispersive solvent
Ultrasound
Cloudy solution
Add salts
Mixture of [CnMIM][PF6] and dual-role solvent
Vortex
Centrifugation
Collection
Aqueous phase
Salts


Nitrogen flow
Mobile phase dilution
Injection

b


Extractant: [CnMIM][PF6]
Disperser: Dual-role solvent
Sample solution
Add extraction and dispersive solvent
Ultrasound
Cloudy solution
Cooling
Ice bath
Centrifugation
Phase sepration
Collection
Supernatant
Sedimented phase
Mobile phase dilution
Injection

c

◀ **Fig. 2** Schematic diagram of three microextraction methods. **a** SILM-DS, **b** SOLM-DS, **c** IL-DLLME. Each step of the SILM-DS procedure is described in the text

and analytes. After sufficient dissolution by vortex mixing and centrifugation, the dispersive solvent was separated from the aqueous phase as a floating upper layer. As a result, the dispersive solvent in the first microextraction step was used as an extraction solvent in the second microextraction step (dual role as disperser and extractor). Because the stratification is relatively stable, pipetting the floating solvent and a small amount of saturated salt solution can be achieved within a few seconds. The separated dual-role solvent was mixed with the first-step extraction solvent (IL phase) and then subjected to HPLC analysis.

SIOM-DS and IL-DLLME procedures

Schematic diagrams of the SIOM-DS (salting-out-enhanced ionic liquid-based one-step microextraction based on dual-role solvent) and IL-DLLME (ionic liquid-based dispersive liquid–liquid microextraction) procedures are shown in Fig. 2b and c. For the SIOM-DS method, 115 μL $[C_8MIM]PF_6$ and 1200 μL dual-role solvent were added to 5 mL of the pretreated milk or environmental water samples (pH 2.0), ultrasonicated for 5 min, 3.0 g Na_2SO_4 added, dissolved by vortex mixing, and finally centrifuged at 4000 rpm for 2 min. The upper organic phase (mixture of dual-role solvent and $[C_8MIM]PF_6$) was collected, blown under a gentle nitrogen flow, dissolved in a set volume of mobile phase, and subjected to HPLC analysis.

For the IL-DLLME method, 115 μL $[C_8MIM]PF_6$ and 1200 μL dispersive solvent were added to 5 mL of the pretreated milk or environmental water sample (pH 2.0), ultrasonicated for 5 min, and centrifuged at 4000 rpm for 5 min. The sedimented $[C_8MIM]PF_6$ was collected, blown under a nitrogen flow, dissolved in a set volume of mobile phase, and subjected to HPLC analysis.

Results and discussion

Optimization of extraction conditions

In order to obtain high extraction efficiency, a series of operational parameters were investigated in detail: sample acidity, type and volume of dual-role organic solvent, type and volume of ILs, ultrasonic extraction time, type and amount of salt, and vortex time.

Effect of sample acidity

The acidity of the aqueous solution plays a key role in SILM-DS procedures because TCs are amphoteric compounds with three functional groups, existing in the form of tetracycline hydrochloride. Thus, pH determines the state of analytes, especially for TCL and DOX, as well as the extraction efficiency of the target compounds. An appropriate acidity should be chosen so that the analytes are removed from the aqueous phase into the extraction solvent in their neutral form [25]. The effect of pH on extraction efficiency was investigated in the range of 2.0–8.0 using HCl and NaOH solution for pH adjustment. No significant changes in extraction recoveries (85–95%) of BPA, TCS, and MTCS were observed as a function of pH, possibly because the analytes were relatively stable in different pH solutions (Fig. 3d). However, recoveries of TCL and DOX decreased sharply from pH 2.0 to 5.0, and then remained constant at ca. 40% for TCL and ca. 55% for DOX from pH 5.0 to 8.0 because their molecular structures were in a neutral form under such conditions. Therefore, pH 2.0 was chosen for the remaining optimization process.

Effects of type and volume of extraction solvent

Characteristics of ILs, such as solubility in water, viscosity, extraction capacity, and chromatographic behavior, play an important role in determining extraction recovery and enrichment factor [26]. It was necessary to take into account the relationship of the extraction recovery and the alkyl-chain length of ILs. On the basis on the above considerations, three hydrophobic ILs were investigated: $[C_4MIM][PF_6]$, $[C_6MIM][PF_6]$, and $[C_8MIM][PF_6]$. Use of $[C_4MIM][PF_6]$ as the extraction solvent resulted in no phase separation between the IL and aqueous solution. Although phase separation occurred when $[C_6MIM][PF_6]$ was used, its extraction recovery was less than that of $[C_8MIM][PF_6]$. This phenomenon can be explained by the high solubility and good dispersive effects of acetonitrile and the weak hydrophobicity of ILs leading to poor or no layering. Moreover, a higher volume of sedimented phase was achieved when using $[C_8MIM][PF_6]$ as the extraction solvent because its solubility was lower than those of $[C_4MIM][PF6]$ and $[C_6MIM][PF_6]$. The solubility of $[C_8MIM]PF_6$ in water is 7.5 mg L^{-1}, which is significantly lower than that of $[C_4MIM]PF_6$ (18.8 mg L^{-1}) [27]. On the basis of these results, $[C_8MIM][PF_6]$ was selected as the extraction solvent in subsequent experiments.

The effect of $[C_8MIM]PF_6$ volume on extraction recovery was studied in the range of 70–145 μL. When the volumes of $[C_8MIM]PF_6$ increased from 70 to 115 μL, the recoveries of the five analytes with contrasting polarities all increased gradually (Fig. 3a). However, at volumes $[C_8MIM]PF_6$ greater than 115 μL, the recoveries decreased gradually except for MTCS which remained constant at ca. 95%. As a result of a certain degree of IL solubility, the larger volume of ILs was accompanied by a larger loss in the sedimented phase, resulting in lower recovery. As a result, 115 μL of

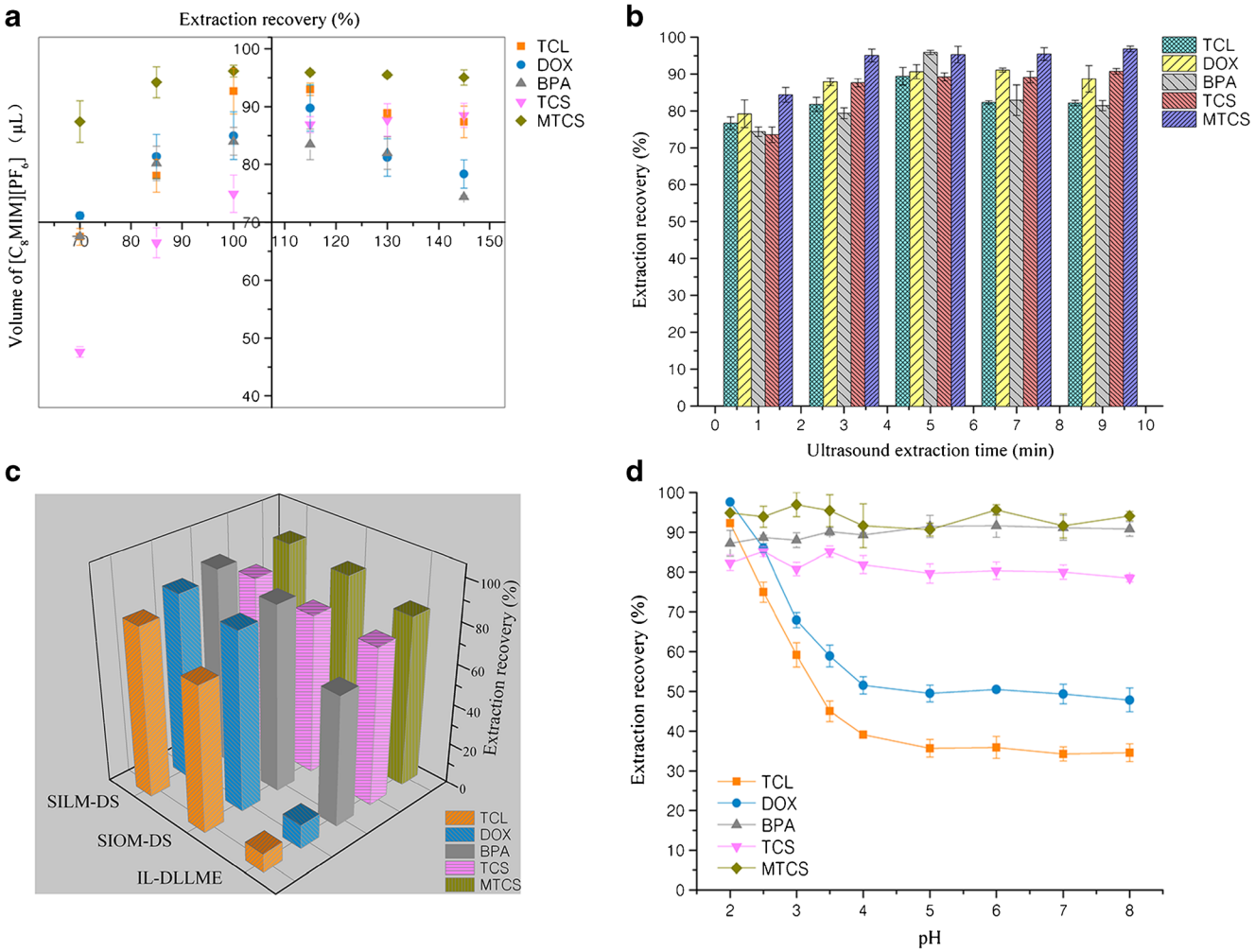


Fig. 3 Effects of **a** extraction solvent volume, **b** ultrasound time, **c** microextraction methods, and **d** sample acidity on recoveries of TCL, DOX, BPA, TCS, and MTCS ($n = 3$). **a** Extraction conditions: dual-role solvent, 1200 μL acetonitrile; pH, 2.0; ultrasound extraction time, 5 min; cooling time, 3 min; 3.0 g Na_2SO_4; vortex extraction time, 3.0 min. **b** Extraction conditions: the same as in **a** (except 115 μL [C_8MIM][PF_6] was added as extraction solvent). **c** Extraction conditions: extraction solvent, 115 μL [C_8MIM][PF_6]; dual-role solvent, 1200 μL acetonitrile; pH, 2.0; 3.0 g Na_2SO_4; vortex extraction time, 3.0 min for SOLM-DS; extraction solvent, 115 μL [C_8MIM][PF_6]; dispersive solvent, 1200 μL acetonitrile; pH, 2.0 for IL-DLLME; 115 μL of extraction solvent; 1200 μL of acetonitrile as the dual-role solvent; pH, 2.0; 5.0 min ultrasound extraction time; 3.0 min cooling time; 3.0 g Na_2SO_4 and 3.0 min vortex extraction time for SILM-DS. **d** Extraction conditions: the same as in **b** (except pH)

[C_8MIM]PF_6 was selected as optimal for extracting analytes in subsequent experiments.

Selection of type and volume of dual-role solvent

Acetone, methanol, acetonitrile, and other polar organic solvents are often utilized as dispersive solvents in traditional dispersive liquid–liquid microextraction procedures. Isopropyl alcohol, acetonitrile, and acetone are three of the most widely used solvents in salting-out-assisted liquid–liquid extraction owing to their miscibility in water at all proportions [28]. On the basis of these considerations, four organic solvents (isopropyl alcohol, ethanol, acetonitrile, and acetone) were evaluated for their potential as a dispersive and salting-out solvent, and their effects on extraction recoveries were compared. In SILM-DS procedures, ethanol, acetonitrile, and acetone had good dispersive effects, but isopropyl alcohol gave a poor dispersion possibly because of its high affinity for ILs. The order of hydrophilicity of the four organic solvents was ethanol > isopropyl alcohol > acetone > acetonitrile. This order determines the salting-out layering effect, i.e., the higher hydrophilicity leads to a higher water content in the upper organic phase. Therefore, excessive hydrophilicity results in a lower enrichment factor, or even a lack of separation in the salting-out process. In our preliminary experiment, methanol gave a better dispersive effect in the first-step microextraction, but no layering phenomenon was observed in the salting-out procedure. In comparison,

isopropyl alcohol, acetone, and acetonitrile all produced a clear layering phenomenon. However, isopropyl alcohol and acetone gave excessive volumes (ca. 1480 and 1350 μL) of upper organic phase (mainly dual-role solvent) in the salting-out procedure, which resulted in difficulty in nitrogen-blowing concentration due to the high water content of the dual-role solvent. As a result, acetonitrile was selected as the dual-role solvent for the SILM-DS procedures.

The extraction recoveries of the five analytes with contrasting polarities showed an increasing trend when the volume of dual-role solvent increased from 800 to 1200 μL (Fig. 4c). This was followed by a decreasing trend in extraction recoveries when the volume of dual-role solvent increased from 1200 to 1400 μL. However, a small increasing trend was observed for TCL and DOX in the 1400–1800 μL range. These findings suggest that when the volume of acetonitrile increased, water content increased sharply leading to increased partitioning of TCL and DOX in the separated upper solvent as a result of their high polarities. In contrast, relatively stable recoveries were observed for BPA, TCS, and MTCS in the volume range of 1400–1800 μL. As a consequence, 1200 μL was selected as the optimal volume for the dual-role solvent.

Selection of ultrasonic extraction time

The SILM-DS procedures involve transferring the analytes from the sample solution to the extractant, which is a time-dependent factor. Extraction recoveries nearly reached their maximum at 3.0 min for MTCS, TCS, and DOX and at 5.0 min for TCL and BPA (Fig. 3b). Recoveries for all five analytes remained constant when the ultrasonic extraction time was longer than 5 min indicating that extraction equilibrium can be achieved within 5.0 min.

Selection of salt type and amount

Salt type directly influences the salting-out effect of the dual-role solvent, and thus optimum salt type selection can enhance separation of the organic phase and improve extraction efficiency [29]. Extraction recoveries for the salts tested followed the order Na_2SO_4 > $(NH_4)_2SO_4$ > $MgSO_4$ > Na_2CO_3 (Fig. 4a). Subsequently, the effect of Na_2SO_4 amount (1.5–4.5 g) on extraction recoveries was investigated. With increasing Na_2SO_4 concentrations, recoveries first increased and then slightly decreased in the range of 3.0–4.5 g (Fig. 4b). These salt dynamics may be explained by larger amounts of salts adsorbing analytes leading to decreased recoveries. The inflection point between increasing and decreasing recoveries was 3.0 g Na_2SO_4, and thus this salt amount was selected for the remaining optimization process.

Selection of vortex extraction time

In SILM-DS procedures, the dual-role water-soluble solvent is separated on the basis of saturated salt solution. Therefore, excess salt should be added to the solution, and its dissolution is affected by many factors such as temperature, vortex time, and salt type. In this investigation, the effect of vortex agitation time on recoveries was examined in the range of 1.0–5.0 min at ambient conditions. Recoveries increased with increasing vortex times until 3 min, and then remained constant (Fig. 4d). Thus, a 3.0-min vortex agitation time was selected as the optimum time in further experiments.

Overall, the optimized SILM-DS parameters are summarized as follows: 115 μL of extraction solvent, 1200 μL of acetonitrile as the dual-role solvent, pH 2.0, 5.0 min ultrasonic extraction time, 3.0 g Na_2SO_4, and 3.0 min vortex extraction time.

Comparison of SILM-DS with SIOM-DS and IL-DLLME

Schematic diagrams for the SILM-DS, SIOM-DS, and IL-DLLME procedures are shown in Fig. 2a–c. After the first-step centrifugation separation in SILM-DS procedures, we observed that about 20 μL [C_8MIM][PF_6] remained in the upper aqueous phase ([C_8MIM][PF_6], initial fortification of 115 μL). This remaining [C_8MIM][PF_6] would be dissolved in the dual-role solvent, i.e., floating on the upper layer in the second-step SAME procedure. After collection of the [C_8MIM][PF_6] layer using a pipette and nitrogen-blowing of the dual-role solvent, the total recovered [C_8MIM][PF_6] volume was ca. 110 μL. Thus, only 5 μL of [C_8MIM][PF_6] was lost throughout the SILM-DS procedures. The final IL volume was relatively stable and prepared for direct analysis by HPLC after appropriate dilution with the mobile phase (ca. 90 μL).

To reduce operational steps, we added the excess salt directly after ultrasonic shaking in SILM-DS procedures, which eliminated the remaining steps of cooling, centrifugation, and collection of ILs in the first-step microextraction. Following vortex mixing and centrifugation, the resulting SIOM-DS was commenced, as shown in Fig. 2b. At a fortification level of 50 μg L^{-1}, the ERs of TCL and DOX were as low as 9.3% and 11.8%, respectively, in the IL-DLLME method. In contrast, SOLM-DS gave 71.5–91.1% ERs for the five analytes, which were significantly higher than those in the IL-DLLME method. Finally, the ERs for the five analytes reached 83.4–93.1% in the SILM-DS method, which were ca. 5.5% higher than average ERs from the SOLM-DS method. These results demonstrate that SILM-DS was the best method for simultaneous extraction and quantification of pollutants with a wide range in polarity (Fig. 3c).

Quality assurance/quality control (QA/QC)

In order to ensure an adequate level of QA and a QC of measurements, the proposed method was utilized for the extraction and determination of the target analytes in some real aqueous samples. First, the repeatability of HPLC–UV measurements was tested on the standard mixture of all target compounds in methanol at a concentration of 500 μg L^{-1}, which corresponded approximately to 19.8 μg kg^{-1} and 20 μg L^{-1} of milks and environmental water samples (5 mL pretreated samples and 200 μL of the finally dissolved volume after the SILM-DS procedures), respectively. At an injection volume of 20 μL, the repeatability for all target compounds, expressed as the relative standard deviation (RSD, %), was calculated to be less than 0.4% for retention time and less than 2.5% for peak area, respectively.

Consequently, the entire method and the optimized instrumental determination step by HPLC–UV were evaluated in the validation study. Blank milk and environmental water samples were artificially contaminated (spiked) with all target compounds. Spiking levels were chosen with regard to real contamination levels and MQLs of 8, 20, and 50 μg L^{-1} for environmental water samples and 7.97, 19.80, and 48.78 μg kg^{-1} for milk samples. The lowest spiking level was selected to cover the concentrations close to the MQL.

To calibrate the SILM-DS method, the mixed standard solutions of five analytes were extracted via the microextraction method. Under optimized experimental conditions, a series of

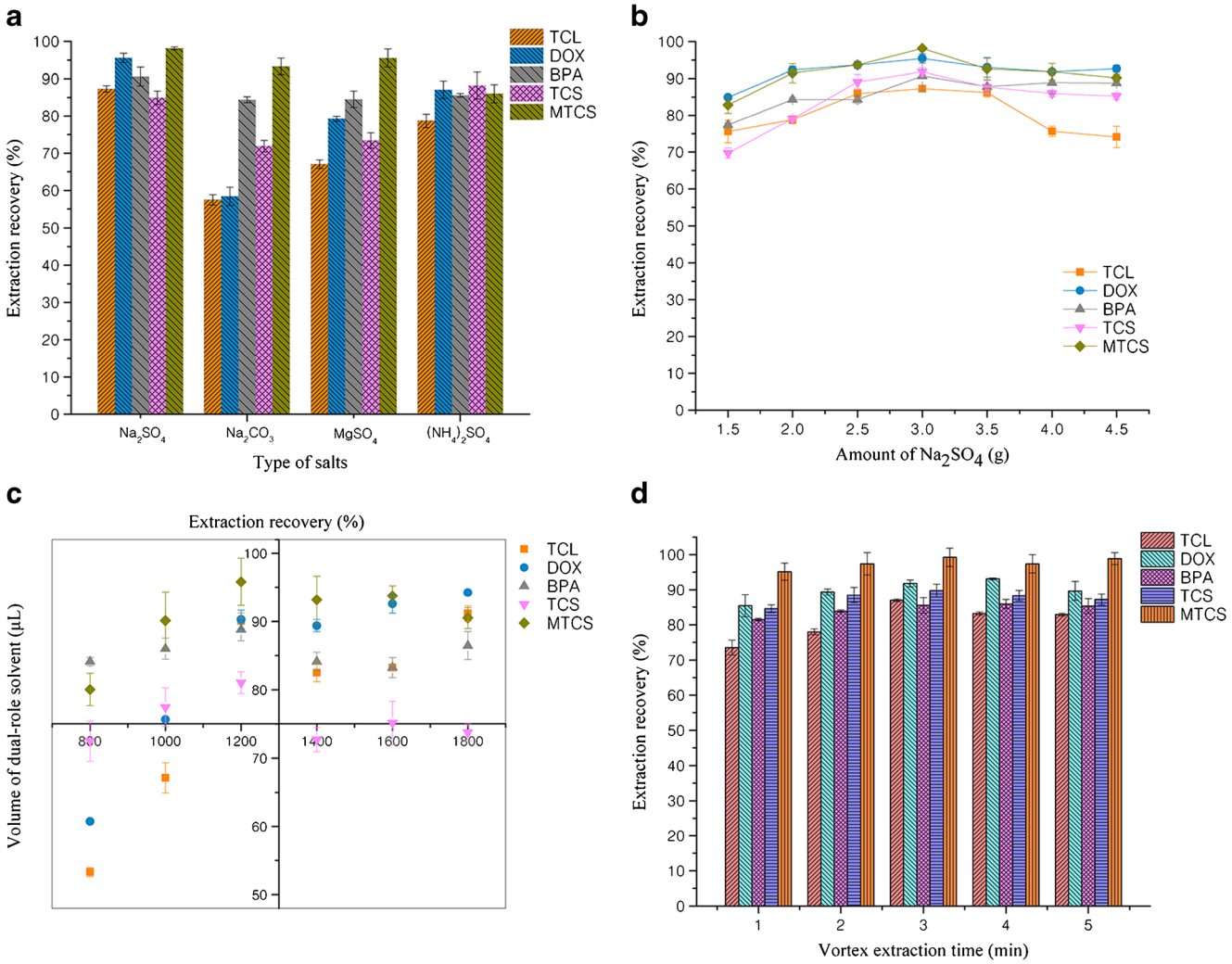


Fig. 4 Effects of **a** salt type, **b** salt amount, **c** dual-role solvent, and **d** vortex time on the extraction recoveries (ERs) of TCL, DOX, BPA, TCS, and MTCS (n = 3). **a** Extraction conditions: extraction solvent, 115 μL [C_8MIM][PF_6]; dual-role solvent, 1200 μL acetonitrile; pH, 2.0; ultrasound extraction time, 5 min; cooling time, 3 min; 3.0 g salt; vortex extraction time, 3.0 min. **b** Extraction conditions: same as in **a** (except amount of Na_2SO_4 was varied). **c** Extraction conditions: same as in **a** (except volume of dual-role solvent was varied). **d** Extraction conditions: extraction solvent, 115 μL [C_8MIM][PF_6]; dual-role solvent, 1200 μL acetonitrile; pH, 2.0; ultrasound extraction time, 5 min; 3 g Na_2SO_4

experiments was conducted to assess the analytical performance of the proposed SILM-DS method. Some analytical metrics such as correlation coefficient (r), linear range (LR), limit of detection (LOD), and limit of quantitation (LOQ) are listed in Table 1. Good linearity was obtained with correlation coefficients (r) of 0.9981–0.9997. The LODs at signal-to-noise ratio (S/N) of 3 for the five analytes ranged from 0.11 to 0.79 μg L^{-1}, and the LOQs at S/N = 10 ranged from 0.36 to 2.63 μg L^{-1} in the environmental water samples. In milk samples, the LODs and LOQs for the five analytes were 0.12–0.75 μg kg^{-1} and 0.39–1.37 μg kg^{-1}, respectively. To evaluate the precision of the developed method, the repeatability of the recovery was investigated in six replicate extractions. Precision experiments were conducted by determining the intra- and interday RSDs at three spiked levels of TCL, DOX, BPA, TCS, and MTCS (48.8/19.8/7.97 μg kg^{-1} in milk and 50/20/8 μg L^{-1} in water; n = 6 for each treatment). The RSDs ranged from 1.4 to 6.4% for intraday analysis and from 2.3 to 6.5% for interday analysis (Table 2).

Analyses of target analytes in aqueous samples

To investigate the practical application of the newly developed SILM-DS method in spiked samples, we analyzed TCL, DOX, BPA, TCS, and MTCS concentrations (log K_{ow} ranged from −1.32 to 5.4) in bovine milk and environmental water samples.

The extraction absolute recovery (AR) was defined as the percentage of the amount of analyte extracted (n_e) relative to that originally present in the sample solution (n_i).

$$\mathrm{AR}(\%) = n_e/n_i \times 100\% \quad (1)$$

Table 1 Analytical performance of the SILM-DS method

Sample	Analyte	Correlation coefficient (r)	Linear range (μg L^{-1}or μg kg^{-1})	LOD (μg L^{-1}or μg kg^{-1})	LOQ (μg L^{-1}or μg kg^{-1})
Whole milk	TCL	0.9981	2.00–200	0.14	0.49
	DOX	0.9987	2.00–200	0.16	0.53
	BPA	0.9994	2.00–200	0.14	0.47
	TCS	0.9987	5.00–500	0.55	1.82
	MTCS	0.9992	5.00–500	0.61	2.01
Low-fat milk	TCL	0.9983	2.00–200	0.13	0.46
	DOX	0.9994	2.00–200	0.21	0.66
	BPA	0.9991	2.00–200	0.22	0.44
	TCS	0.9993	5.00–500	0.74	1.46
	MTCS	0.9996	5.00–500	0.75	1.37
Nonfat milk	TCL	0.9985	2.00–200	0.12	0.39
	DOX	0.9982	2.00–200	0.14	0.47
	BPA	0.9993	2.00–200	0.13	0.44
	TCS	0.9990	5.00–500	0.51	1.68
	MTCS	0.9995	5.00–500	0.56	1.85
Sea water	TCL	0.9994	2.00–200	0.11	0.36
	DOX	0.9993	2.00–200	0.13	0.44
	BPA	0.9995	2.00–200	0.12	0.41
	TCS	0.9992	5.00–500	0.59	1.96
	MTCS	0.9994	5.00–500	0.77	2.57
WRTR water	TCL	0.9997	2.00–200	0.13	0.42
	DOX	0.9993	2.00–200	0.16	0.53
	BPA	0.9991	2.00–200	0.15	0.50
	TCS	0.9992	5.00–500	0.56	1.85
	MTCS	0.9994	5.00–500	0.75	2.49
Tap water	TCL	0.9995	2.00–200	0.15	0.51
	DOX	0.9993	2.00–200	0.18	0.60
	BPA	0.9997	2.00–200	0.17	0.57
	TCS	0.9993	5.00–500	0.55	1.84
	MTCS	0.9998	5.00–500	0.79	2.63

r correlation coefficient, *LR* linear range, *LOD* limit of detection (S/N = 3), *LOQ* limit of quantitation (S/N = 10)

Table 2 Intraday and interday precision of the proposed SILM-DS method

Analytes	Intraday precision (RSD%, n = 6)			Interday precision (RSD%, n = 6)		
	Low	Medium	High	Low	Medium	High
TCL	2.2	3.0	2.5	6.0	3.6	5.0
DOX	3.9	1.4	2.6	5.8	6.5	4.3
BPA	3.9	2.6	2.5	4.8	2.3	2.6
TCS	5.9	6.4	3.3	4.5	6.4	3.3
MTCS	5.2	5.7	2.2	6.2	5.6	3.3

"High" indicates 48.78 μg kg^{-1} for milks and 50 μg L^{-1} environmental waters; "medium" indicates 19.80 μg kg^{-1} for milks and 20 μg L^{-1} environmental waters; "low" indicates 7.97 μg kg^{-1} for milks and 8 μg L^{-1} environmental waters

Considering the expanded uncertainty of extraction recovery (ER) results, it is described as follows:

$$\mathrm{ER}(\%) = \mathit{Mean}(\mathrm{AR}\%) \pm \mathrm{SD} \quad (2)$$

where SD indicates standard deviation and Mean (AR%) denotes the average of AR% (n = 6).

In addition, several of the main elements of uncertainty were taken into account when optimizing and validating this method, such as the detected amount in spiked samples, the recovery by this proposed SILM-DS procedure, and the related precision characterized by RSD [30].

Typical chromatograms for blank and spiked milk (48.8 μg kg^{-1}) and environmental water (50 μg L^{-1}) samples are shown in Figs. 5 and 6, respectively. Only BPA was detected in the range of 3.34–5.24 μg L^{-1} in blank (non-spiked) sea water samples (Table 3). Extraction recoveries for spiked samples were in the range of 81.8–105.8% for TCL, 87.5–103.9% for DOX, 86.9–106.9% for BPA, 90.0–103.8% for MTCS, and 74.5–88.3% for TCS in milk and environmental water samples (Table 3). The LODs of the five analytes were in the range of 0.12–0.75 μg kg^{-1} for milk samples and 0.11–0.79 μg L^{-1} in environmental water samples. These results demonstrate the efficacy of the newly developed SILM-DS method for simultaneously detecting trace pollutants with a large range of polarities in aqueous samples with high precision and accuracy.

Comparison of SILM-DS with other methods

To our knowledge, the newly developed SILM-DS method combined with HPLC–UV is the first one to provide simultaneous TCL, DOX, BPA, TCS, and MTCS quantification (log K_{ow} range −1.32 to 5.4) in aqueous samples. So far, there is a paucity of methods for the simultaneous detection of multiple coexisting contaminants with a wide range of polarities, and the few available reports are mainly related to SPE because of the unique properties of SPE sorbents such as surfactant-modified sorbent and silica-based octadecyl (C_{18}) [31–33].

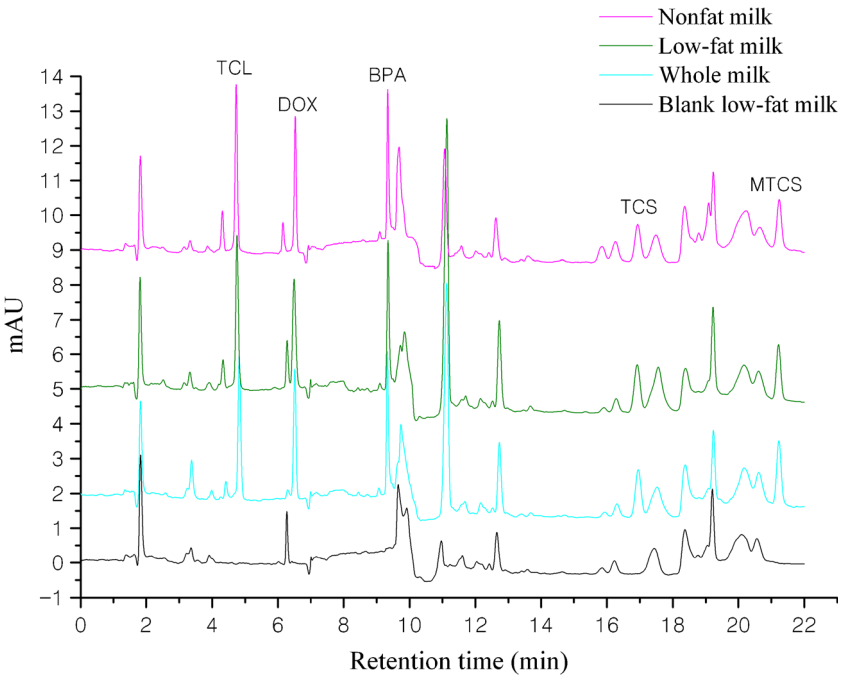


Fig. 5 Chromatograms of five analytes in milk samples obtained by the SILM-DS–HPLC–UV method. The fortified level of TCL, DOX, BPA, TCS, and MTCS was 48.78 μg kg^{-1} in milk samples. Optimized conditions: 115 μL of extraction solvent; 1200 μL of acetonitrile as the dual-role solvent; pH, 2.0; 5.0 min ultrasound extraction time; 3.0 min cooling time; 3.0 g Na_2SO_4 and 3.0 min vortex extraction time

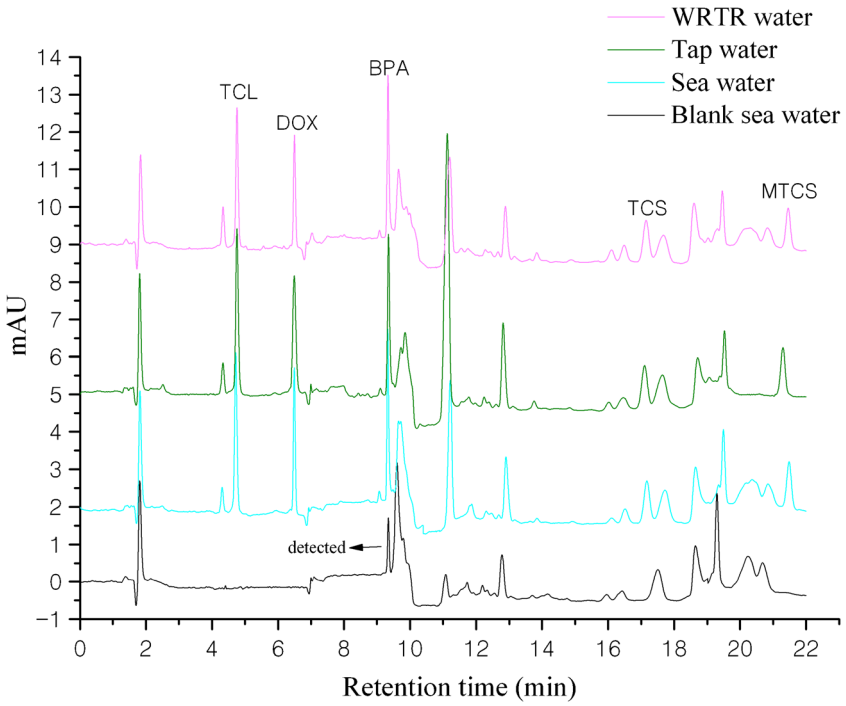


Fig. 6 Chromatograms of five analytes in environmental water samples obtained by the SILM-DS–HPLC–UV method. The fortified levels of TCL, DOX, BPA, TCS, and MTCS was 50 μg L^{-1} in water samples. Optimized conditions: 115 μL of extraction solvent; 1200 μL of acetonitrile as the dual-role solvent; pH, 2.0; 5.0 min ultrasound extraction time; 3.0 min cooling time; 3.0 g Na_2SO_4 and 3.0 min vortex extraction time

Hemimicelles and admicelles are structures formed from solutions of ionic surfactants, which can be sorbed on the surfaces of active solids, resulting in sorbents capable of simultaneously extracting a wide range of analytes with extremely varied polarity, thus this almost unique property renders such surfactant-based solid SPE sorbents potentially invaluable in multi-residue extraction methods [31, 32]. Moral and coworkers proposed the ASPE (admicellar solid-phase extraction)–LC/UV method, which employed SPE cartridges packed with SDS/tetrabutylammonium chloride (TBACl) hemimicelles and admicelles adsorbed on c-alumina to extract 17 pesticides with different polarities (log K_{ow} from 1.5 to 3.6) with varying classes from aqueous environmental samples. However, the aforementioned method gave low recoveries (only 21–42%) for some high polarity compounds with log K_{ow} of 2.9 or less, and also a large amount of organic solvent was required for the elution procedure [32]. Mirnaghi et al. [33] employed SPE cartridges packed with C_{18} to isolate compounds with a wide range of polarities (log K_{ow} from 0.14 to 4.98) in phosphate buffered saline (PBS) before LC–MS analysis. However, the reported polarity range suitable for the above method is relatively narrower (0.14–4.98) as compared with those (−1.32 to 5.40) suitable for this SILM-DS method. Moreover, the method proposed by Mirnaghi and coworkers was only used in PBS solution, not in real samples. The recoveries for analytes were higher (92–105%) in 1 mL of 20 μg L^{-1} PBS sample solution, but lower (15–44%) for some high polar analytes in 25 mL of 2 μg L^{-1} PBS sample solution, suggesting that when the sample volume exceeds the retention capacity of the sorbent, the target analytes are not quantitatively retained by the sorbent any more, resulting in a large loss of recovery. Consequently, the ordinary C_{18}-SPE or C_8-SPE cartridges cannot satisfy the technical requirements for the simultaneous extraction of multiple analytes with a wide range of polarities because of the limitation of extraction capacity and the polar limitation of cartridge materials [33]. Tabani and coworkers introduced agarose gel as a green membrane for the extraction of drugs with a wide range of polarities; although the method is environmentally friendly, the operational procedures are very complex, leading to a high cost and low recoveries for the analytes. In particular, a prerequisite of this method is that the target analytes must possess like-charges under a constant pH value [34].

Table 4 provides a comparison of the proposed SILM-DS method with other commonly used methods for the determination of TCL, DOX, BPA, TCS, or MTCS in milk or environmental water samples. The RACNTs–HPLC–DAD method (restricted access carbon nanotubes, column switching) achieved LODs of 7.5–13.2 μg kg^{-1} and recoveries of 47.0–69.6% for determination of TCL and DOX in milk, which represents significantly lower sensitivity and recoveries compared to the SILM-DS method (LODs, 0.12–0.16 μg kg^{-1}; recovery, 81.8–105.8%) [35]. The MSPE–HPLC–UV method (magnetic solid-phase extraction) attained an extraction recovery of 81% and a LOD of 0.75 μg L^{-1} for BPA in cow milk, which were comparable with those in this investigation [36]. Azzouz and coworkers utilized SPE (solid-phase extraction)–GC/MS for quantification of BPA and TCS in breast milk with LODs of 1.0 ng L^{-1} and 1.3 ng L^{-1}, respectively [37]. Although the SPE–GC/MS provided a lower LOD, it required long pretreatment time (>3 h) and more expensive GC/MS instrumentation than the HPLC used in this study. Wang

Table 3 Analytical performance for TCL, DOX, BPA, TCS, and MTCS in milk and environmental water samples (mean ± SD, $n = 6$)

Analytes	Whole milk				Low-fat milk				Nonfat milk				Sea water
	Blank	Added (μg kg^{-1})	Found (μg kg^{-1})	ER (%)	Blank	Added (μg kg^{-1})	Found (μg kg^{-1})	ER (%)	Blank	Added (μg kg^{-1})	Found (μg kg^{-1})	ER (%)	Blank
TCL	ND	7.97	7.26 ± 0.16	91.12 ± 2.01	ND	7.97	7.29 ± 0.12	91.45 ± 1.51	ND	7.97	8.19 ± 0.31	102.70 ± 3.89	ND
	ND	19.80	16.22 ± 0.56	81.91 ± 2.83	ND	19.80	17.01 ± 0.65	85.88 ± 3.28	ND	19.80	20.94 ± 0.53	105.77 ± 2.68	ND
	ND	48.78	39.88 ± 0.96	81.75 ± 1.97	ND	48.78	42.05 ± 1.04	86.20 ± 2.13	ND	48.78	50.66 ± 0.95	103.86 ± 1.95	ND
DOX	ND	7.97	7.44 ± 0.27	93.33 ± 3.39	ND	7.97	7.66 ± 0.46	96.11 ± 5.77	ND	7.97	8.28 ± 0.31	103.89 ± 3.89	ND
	ND	19.80	17.43 ± 0.24	88.01 ± 1.21	ND	19.80	19.54 ± 0.77	98.67 ± 3.89	ND	19.80	18.61 ± 0.57	94.00 ± 2.88	ND
	ND	48.78	42.67 ± 1.09	87.47 ± 2.23	ND	48.78	48.93 ± 0.76	100.3 ± 1.56	ND	48.78	46.05 ± 0.32	94.40 ± 0.66	ND
BPA	ND	7.97	7.44 ± 0.27	93.33 ± 3.39	ND	7.97	7.53 ± 0.43	94.44 ± 5.40	ND	7.97	7.66 ± 0.31	96.11 ± 3.89	3.34 ± 0.37
	ND	19.80	19.27 ± 0.47	97.33 ± 2.37	ND	19.80	19.27 ± 0.51	97.33 ± 2.58	ND	19.80	19.49 ± 0.39	98.44 ± 1..97	4.24 ± 0.57
	ND	48.78	43.45±1.05	89.07 ±2.15	ND	48.78	45.53±1.02	93.33 ±2.09	ND	48.78	42.40±0.56	86.93 ±1.15	5.24±0.67
TCS	ND	7.97	6.46±0.35	81.08 ±4.39	ND	7.97	6.66±0.44	83.58 ±5.52	ND	7.97	6.98±0.45	87.60 ±5.65	ND
	ND	19.80	15.54±0.19	78.47 ±0.96	ND	19.80	14.75±0.61	74.47 ±3.08	ND	19.80	16.17±0.58	81.68 ±2.93	ND
	ND	48.78	36.71±0.86	75.26 ±1.76	ND	48.78	43.05±0.71	88.25 ±1.46	ND	48.78	40.69±0.39	83.41 ±0.80	ND
MTCS	ND	7.97	7.68±0.49	96.30 ±6.15	ND	7.97	7.19±0.54	90.20 ±6.78	ND	7.97	8.37±0.48	98.13 ±6.02	ND
	ND	19.80	19.07±0.99	96.29 ±5.00	ND	19.80	18.19±0.82	91.85 ±4.14	ND	19.80	19.07±0.59	96.30 ±2.98	ND
	ND	48.78	44.23±0.82	90.67 ±1.68	ND	48.78	46.06±0.65	94.42 ±1.33	ND	48.78	45.38±0.93	93.03 ±1.91	ND

Analytes	Sea water			WRTR water				Tap water			
	Added (μg L^{-1})	Found (μg L^{-1})	ER (%)	Blank	Added (μg L^{-1})	Found (μg L^{-1})	ER (%)	Blank	Added (μg L^{-1})	Found (μg L^{-1})	ER (%)
TCL	8	7.22 ± 0.32	90.64 ± 4.00	ND	8	7.36 ± 0.30	92.39 ± 3.75	ND	8	7.19 ± 0.18	90.16 ± 2.25
	20	18.52 ± 0.34	93.56 ± 1.70	ND	20	17.86 ± 0.40	90.22 ± 2.00	ND	20	18.06 ± 0.54	91.23 ± 2.70
	50	43.13 ± 0.95	88.42 ± 1.90	ND	50	45.38 ± 0.68	93.04 ± 1.36	ND	50	47.39 ± 0.65	97.15 ± 1.30
DOX	8	7.30 ± 0.42	91.61 ± 5.25	ND	8	7.91 ± 0.42	99.29 ± 5.25	ND	8	8.01 ± 0.25	100.47 ± 3.13
	20	18.54 ± 0.88	93.62 ± 4.40	ND	20	18.54 ± 0.73	93.62 ± 3.65	ND	20	19.71 ± 0.67	99.53 ± 3.35
	50	44.00 ± 0.92	90.21 ± 1.84	ND	50	47.60 ± 0.92	97.59 ± 1.84	ND	50	47.74 ± 0.67	97.87 ± 1.34
BPA	8	8.61 ± 0.34	93.01 ± 4.25	ND	8	6.92 ± 0.36	86.87 ± 4.50	ND	8	8.52 ± 0.49	106.85 ± 6.13
	20	18.21 ± 0.66	91.98 ± 3.30	ND	20	18.00 ± 0.89	90.91 ± 4.45	ND	20	18.17 ± 0.41	91.75 ± 2.05
	50	44.05±0.86	87.31 ±1.72	ND	50	45.96±0.56	94.21 ±1.12	ND	50	46.23±0.52	94.77 ±1.04
TCS	8	6.75±0.38	84.70 ±4.75	ND	8	6.27±0.38	78.69 ±4.75	ND	8	6.84±0.38	85.79 ±4.75
	20	15.59±0.21	78.75 ±1.05	ND	20	16.09±0.63	81.26 ±3.15	ND	20	15.58±0.42	78.69 ±2.10
	50	40.19±0.67	82.39 ±1.34	ND	50	37.60±0.54	77.08 ±1.08	ND	50	38.59±0.38	79.11 ±0.76
MTCS	8	7.64±0.56	95.83 ±7.00	ND	8	8.28±0.45	103.84 ±5.63	ND	8	7.72±0.57	96.91 ±7.13
	20	18.15±0.74	91.67 ±3.70	ND	20	19.52±0.34	98.61 ±1.70	ND	20	19.90±0.91	100.49 ±4.55
	50	43.90±0.87	90.00 ±1.74	ND	50	46.67±0.82	95.67 ±1.64	ND	50	45.09±0.89	92.44 ±1.78

ER extraction recovery, *SD* standard deviation, *Blank* sample unfortified with TCL, DOX, BPA, TCS, and MTCS standards

Table 4 Comparison of the proposed method with the previous methods for determination of TCL, DOX, BPA, TCS, and MTCS in milk and environmental waters

Analytical method	Analyte	Preparation procedures	Volume of organic solvent (mL)	LOD (μg kg^{-1} or μg L^{-1})	LOQ (μg kg^{-1} or μg L^{-1})	Matrix	Recoveries	References
RACNTs–HPLC–DAD	TCL and DOX	Agitation (25 °C, 30 min), centrifugation (10 min), HPLC analysis	0	7.5–13.2	–	Milks	47.0–69.6%	[35]
MSPE–HPLC–UV	BPA	Sonication (15 min), removing the supernatant by magnet separation, sonication (4 min), collection of the supernatant, and HPLC analysis	0.5	0.75	–	Cow milk	81%	[36]
SPE–GC/MS	BPA and TCS	Vortex (2 min), centrifugation (10 min), filtering, evaporation, and redissolution by GC/MS analysis	2.0	0.001 and 0.0013	–	Breast milk	–	[37]
ASE–GPE–GC/MS[a]	TCS	Description as below in note section	>30	–	3.5	Human breast milk	82.4%	[38]
DLLME–GC–MS/MS	TCS and MTCS	Shaking manually (1 min), centrifugation (5 min), GC–MS/MS analysis	>2.0	–	0.002 and 0.005	Water samples	79.3 ± 6.8%, 72.9 ± 8.2%	[39]
SILM-DS–HPLC–UV	TCL, DOX, BPA, TCS, and MTCS	Ultrasonic mixing (5 min), cooling, centrifugation (5 min), vortex mixing (3 min), centrifugation (2 min), HPLC analysis	1.2	0.11–0.79	0.36–2.63	Milks and environmental waters	74.5–106.9%	This work

LOD and LOQ indicate limit of detection (S/N = 3) and limit of quantitation (S/N = 10), respectively

RACNTs restricted access carbon nanotubes, column switching, *MSPE* magnetic solid-phase extraction, *SPE* solid-phase extraction, *ASE–GPE* accelerated solvent extraction combined with gel permeation chromatography, *DLLME* dispersive liquid–liquid microextraction

[a] ASE–GPE–GC/MS analytical procedures: First, the extraction cell was heated to 120 °C and filled with the solvent until the pressure reached 1500 psi (10.34 MPa). After an oven heat-up time of 6 min, two static extractions at constant pressure and temperature of 8 min were performed. After the static period, fresh solvent was introduced to flush the lines and cell, and the extract was collected in a 60-mL glass vial. The residue solvent in the cell was purged into the collection vial with pressurized nitrogen. The crude extracts of about 30 mL were concentrated to near dryness with a rotary evaporator in a temperature-controlled bath (38 °C) and the lipids were weighed and redissolved with 5 mL EA/cyclohexane (1:1, v/v) for GPC using a J2 Scientific packed glass column (225 mm × 2.0 mm i.d., J2 Scientific). The mobile phase was a mixture of EA/cyclohexane (1:1, v/v) at a flow rate of 5 mL/min. After discarding the first 42.5 mL elution, the following 50 mL was collected and concentrated with a rotary evaporator to near dryness, and redissolved with 5 mL of cyclohexane for further purification by a Sep-Pak Florisil cartridge (500 mg, 6 mL) preconditioned with 6 mL 10% EA in pentane. The target analytes were eluted using 15 mL 10% EA in pentane. The extract was concentrated to near dryness after adding 0.5 mL isooctane as keeper. Then 200 g phenanthrene-d_{10} per liter was added to the final sample and brought to 0.5 mL for GC–MS/MS analysis

et al. [38] reported on the ASE–GPE–GC/MS method (accelerated solvent extraction combined with gel permeation chromatography) for determination of TCS in human breast milk with LOQ of 3.5 μg kg^{-1}, recovery of 82.4%, and RSDs less than 20%, which represent higher LOQ and lower recovery compared to the newly developed method. Besides, a large amount of organic solvent was required during the analysis of the extracts [38]. The DLLME–GC–MS/MS method applied to the simultaneous derivatization and concentration of TCS and MTCS in water samples attained recoveries of 79.3% and 72.9% for TCS and MTCS, respectively, which were appreciably lower than those obtained by the SILM-DS method [39]. The detailed advantages and disadvantages of the aforementioned methods are summarized in Table S1 (see Electronic Supplementary Material, ESM) through a series of appraising indexes such as cost, green aspect, extraction time, operational procedure, and so on. Importantly, the newly proposed SILM-DS method can simultaneously determine pollutants across a wide range of polarities resulting in a considerably reduced workload for ordinary environmental monitoring and food tests of organic pollutants. Thus, the newly proposed SILM-DS method has great potential for determination of trace-level concentrations of organic pollutants with a wide range of polarities in several analytical fields.

Conclusions

The proposed SILM-DS method combines the advantages of IL-based dispersive liquid–liquid microextraction and salting-out effect to achieve high extraction efficiencies for simultaneous determination of trace occupational pollutants with a wide range of polarities. The disperser in the first-step microextraction was converted to the extractant in the subsequent salting-out microextraction procedure, and thus one solvent performed a dual role as both extractant and disperser in the SILM-DS process. Under optimized conditions, the proposed method gave reasonable ERs (74.5–106.9%) and low LODs (0.11–0.79 μg kg^{-1}) for five pollutants with a log K_{ow} range from −1.32 to 5.40 in complex milk and environmental water matrices. Besides simple operation, low cost, environmental friendliness, and no requirement for expensive instrumentation, the most prominent advantage for this SILM-DS method is the simultaneous detection of coexisting environmental and food pollutants with varying polarities. Therefore, it can substantially reduce the workload for ordinary environmental monitoring and food tests of organic pollutants, which has a great application value in the detection of multiple occupational trace pollutants with a wide range of polarities.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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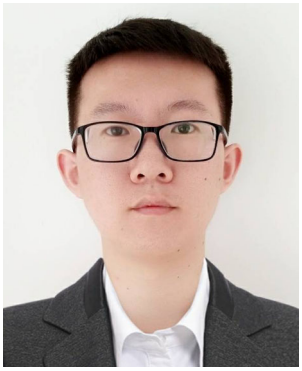

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