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Screening and Optimization of Microextraction of Pb(II) by Inductively Coupled Plasma-Atomic Emission Using Response Surface Methodology

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Abstract

Dispersive liquid–liquid microextraction (DLLME) combined with inductively coupled plasma-atomic emission spectrometry (ICP-AES) was applied for the determination of lead in different environmental water samples. Ammonium pyrrolidine dithiocarbamate (APDC), chloroform and ethanol were used as chelating agent, extraction solvent and disperser solvent, respectively. The effective parameters, such as volume of extraction and disperser solvents, sample volume, pH, salt effect, extraction time, centrifuge speed and amount of chelating agent were optimized with the aid of response surface methodology (RMS) and experimental design. Plackett-Burman design (PBD) was used to choose the significance variables for the optimization. The significant factors were optimized using a central composite design (CCD) then a quadratic model between the dependent and the independent variables was built. The proposed method showed good coincidence between the experimental data and predictive value, and it has been successfully employed to determine lead in environmental water samples. The limit of detection was 8 ngmL^{-1} and, repeatability of the method, described as relative standard deviation, was 5.7% (n = 5).

Keywords: *Dispersive liquid-liquid microextraction, Response surface methodology, Plackett-Burman design, Central composite design, Pb , Environmental water samples.*

Introduction

Lead (Pb), as an environmental pollutant, reaches humans from natural as well as anthropogenic sources, e.g., drinking water, soils, industrial emission, car exhaust, contaminated food, beverages, etc. It's known to cause adverse health effects in humans even following long-term exposure to low doses

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[1]. It is well documented that lead can disturb hemoglobin synthesis and cause behavioral and neurologic disturbances [2]. Long-term exposures to low lead concentrations can cause *Tubular Proteinuria*, bone damage [3], effects on renal function and blood pressure [4].

Various instrumental techniques including: flame atomic absorption spectroscopy [5,6], voltammetry [7], total reflection x-ray fluorescence (TXRF) [8], inductively coupled plasma atomic emission spectrometry [9, 10] etc. have been used for the determination of lead in environmental samples. The levels of Pb in the environmental samples are generally lower than the detection limits of these techniques. Although lower detection limits can be achieved with powerful analytical methods, such as graphite furnace atomic absorption spectrometry (GF-AAS) [11, 12] inductively coupled plasma-mass spectrometry (ICP-MS) [13], electrothermal vaporization inductively coupled plasma-mass spectrometry ((ETV-ICP-MS) [14], but an initial sample pretreatment such as pre-concentration of the trace element and matrix separation, is often necessary and many analytical laboratories cannot support such equipment because of their high price and expensive maintenance. To solve these problems, pre-concentration-separation techniques including liquid–liquid extraction (LLE) [15], liquid phase microextraction (LPME) [16], solid phase extraction (SPE) [17], solid phase microextraction (SPME) [18], ion-exchange [19], hydride generation [20], co-precipitation [21] etc., have been proposed. Dispersive liquid-liquid microextraction (DLLME), that proposed by Assadi and coworkers [16], is a miniaturized sample pretreatment technique. In this method, cloudy solution is formed after injecting the appropriate mixture of extraction solvent and disperser solvent rapidly into the aqueous sample by syringe. The outstanding advantages of DLLME are its simplicity of operation, rapidity, inexpensive, high recovery and enrichment factor [22].

In our previous paper, we reported optimization of Cd(II) in different water samples by DLLME preconcentration and inductively coupled plasma-atomic emission spectrometry (ICP-AES) determination [23]. In the present work, DLLME followed ICP-AES has been investigated for determination of Pb(II) in environmental water samples. The main goal of the proposed work was to describe in details the effects of various parameters in order to build a model to achieve high enrichment factor and recovery and useful amount of sedimented phase volume as responses. The influence of each of the parameters and their interactions could be well identified for different responses screened. The use of an experimental design enabled a subsequent benefit in terms of labor time and number of experience to optimize the conditions.

Experimental

Instrumentation

An ICP-AES instrument, Model Optima 2100DV, Perkin Elmer, equipped with a CCD detector and a Rotofix 32 centrifuge from Zentrifugen Co were used. The pH values were measured with a Mettler Toledo pH/Ion-Analyzer, Model MA235, supplied with a glass-combined electrode. Table 1 showed the instrumental and operating conditions for ICP-AES measurements.

Reagents

The stock solution of Pb (1000 mgL^{-1} for ICP-AES standard) from Merck (Darmstadt, Germany) were used in this work. All working solutions were prepared by diluting the stock standards as necessary. Deionized distilled water obtained with a Milli-Q system (Millipore, Milford, USA) was used for standard dilutions and other necessary preparations. The chelating agent, 0.1M ammonium pyrrolidine dithiocarbamate (APDC) solution, was prepared daily, on a hot-plate stirrer at approximately 50°C, by dissolving the appropriate amount of APDC (analytical grade, Merck) in ethanol (extra pure, Merck). The rest of the used chemicals were carbon tetrachloride (extra pure), chloroform (extra pure) and dichloromethane (extra pure) as extraction solvent, methanol (for liquid chromatography), acetone (extra pure) and acetonitrile (HPLC grade) as disperser solvent, HNO_3 (65%, supra pure), CH_3COONa (supra pure), $NaNO_3$ (analytical grade) and NH_4OH(25%, supra pure) supplied by Merck.

Dispersive liquid–liquid microextraction procedure

To 5mL of 1 mgL^{-1} Pb^{+2} solution in a 12-mL test tube with conical bottom, 1.5mL of ethanol (disperser solvent) contains 200μL of chloroform (extraction solvent) and 0.1M APDC (chelating agent) was injected rapidly into the sample solution by using 2mL syringe. The mixture was immediately centrifuged for 5min at 1000rpm. The volume of the sedimented phase (chloroform) was determined using a 200μL HPLC syringe.

Table 1. Operation parameters for ICP-AES.

Parameters	
RF Power (watt)	1300
Nebulizer gas flow rate (Lmin^{-1})	0.8
Auxiliary gas flow rate (Lmin^{-1})	0.2
Plasma gas flow rate (Lmin^{-1})	15
Sample flow rate (Lmin^{-1})	1.2
Wavelength (nm)	220.353
Plasma viewing	Axial
Processing mode	Area
Delay time (sec)	20

The sedimented phase was quantitatively transferred to another test tube and allowed to evaporate at room temperature. The residue was dissolved into 0.5mL of 0.1M nitric acid and the lead concentration was determined by ICP-AES. Lead standard solutions (0.2–10 mgL^{-1}) in 0.1M nitric acid were prepared daily. All experiments were performed in duplicate and the mean of results was used in plotting curves or preparation of tables for optimization.

Statistical software

Essential Regression and Experimental Design for Chemists and Engineers, EREGRESS, as a Microsoft Excel Add-In software was used to design the experiments and to model and analyze the results [24].

Experimental design nomenclature

The objective of the experimental design was to determine the main parameters influencing the efficiency factor, as well as recovery and sedimented phase of the DLLME method. The most important DLLME variables including: volume of extraction solvent (F_1), volume of dispersive solvent (F_2), pH (F_3), salting effect (F_4), chelating agent (F_5), sample volume (F_6), extraction time (F_7) and centrifuge speed (F_8) were selected and preliminary tests undertaken to assess the tendencies of the factors and which had the greatest influence on efficiency factor of lead. A Plackett-Burman factorial design with two levels (low and high) was set up in duplicate. For each the most significant parameters were then selected to generate a central composite design in order to build a predictive model (response surface model: RSM) of the three responses including: efficiency factor (EF), recovery (R) and sedimented phase volume (Vs). Then, the factors studied were chosen to build a model for prediction of optimum condition for each response.

Results and Discussion

Selection of extraction and dispersive solvents

Three criteria should be meet the selection of extraction solvent: a) it should dissolve analyte better than water b) it should be heavier than water and c) it should form tiny droplets when it is added to the aqueous solution of analyte along with a extraction solvent. Chloroform ($CHCl_3$), carbon tetrachloride (CCl_4) and dichloromethane (CH_2Cl_2) were studied as extraction solvent for lead.

For the DLLME method, miscibility of disperser solvent with extraction solvent and aqueous phase (sample solution) is the main point for the selection of dispersive solvent. Four solvents including: ethanol, methanol, acetone and acetonitrile were investigated as dispersive solvent. In Figure 1 the efficiency factor (EF) is shown for all combinations of dispersive and extraction solvents.

For dichloromethane as extraction solvent two-phase system was just observed by acetone as dispersive solvent, on the other hand for methanol, ethanol or acetonitrile as dispersive solvents no sedimented phase was obtained and hence these conditions are useless. Considering the sedimented phase volume it was found that with the combination of chloroform and carbon tetrachloride with methanol the sedimented phase volume was about 370µL and with acetonitrile the sedimented phase volume was about 480µL, therefore these combinations had low efficiency factor. Chloroform with acetone showed attainable recovery but it showed low EF.

Among these different combination of extraction and dispersive solvents, chloroform-ethanol showed the highest efficiency and reasonable recovery, therefore, chloroform and ethanol were selected as the extraction and dispersive solvents (Figure 1) respectively.

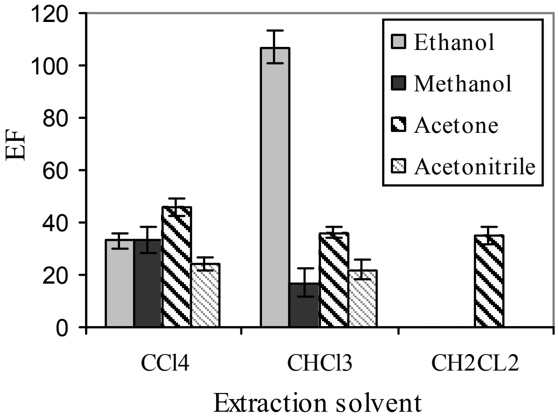

Figure 1. Selection of extraction and disperser solvents in DLLME Conditions: sample, 5mL Pb^{+2} 0.5µgmL^{-1}; volume of dispersive solvent, 2mL; volume of extracting solvent, 200µL; pH= 4 and APDC 0.1M. The bars show the maximum and minimum levels of determinations.

Optimization of dispersive liquid–liquid microextraction

Plackett-Burman factorial design

Plackett-Burman factorial design is a screening design that involves a large number of factors and relatively few runs so it can estimate only main effects. Due to its simplicity and relatively low cost, PBD is useful for preliminary studies or in the initial steps of an optimization [25, 26].

In this work, eight effective parameters including: volume of extraction (F_1) and disperser solvents (F_2), pH (F_3), salt effect (F_4), chelating agent (F_5), sample volume (F_6), extraction time (F_7) and centrifuge speed (F_8) were selected as independent variables. A Plackett-Burman factorial design (involving 12 experiments, 8 factors) with three center points was selected, allowing 3 degrees of freedom (number of runs-number of factors-number of center points^{-1}) which involve 15 nonrandomized runs. In order to test the statistical significance of the effects, an ANOVA system was employed by EREGRESS, as Microsoft Excel Add-In software. Independent variables, their levels and symbols and the design matrix and the efficiency factor (EF) for PBD were shown in Table 2 and 3 respectively. The p-value of the variable was at 5% level ($p<0.05$), when it was considered to have a greater impact on the enrichment factor. Out of 8 variables studied, 3 variables (sample volume (F_6), volume of extraction solvent (F_1) and volume of dispersive solvent (F_2)) had significant influence on efficiency factor by their p-value ($p<0.05$, significant at 5 % level), obtained from the regression analysis.

Table 2. Independent variables, their levels and symbols for PBD.

Variable	**Variable Symbol**	**Variable levels**		
		-1	**1**	**CP***
Volume of extraction solvent (µl)	F_1	100	500	300
Volume of dispersive solvent (ml)	F_2	2	4	0
pH	F_3	2	10	6
Salting effect (%, w/v)	F_4	0	10	3
Chelating agent (M)	F_5	0.002	0.1	0.002
Sample Volume(ml)	F_6	5	25	15
Extraction time (min)	F_7	0	60	30
Centrifuge Speed (rpm)	F_8	1000	5000	3000

*CP: Center Points

Table 3. Design matrix and the response for PBD.

Run No	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**EF**
1	1	1	-1	1	1	-1	1	-1	0
2(CP)	0	0	0	0	0	0	0	0	67.75
3	1	-1	1	1	-1	1	1	-1	82
4(CP)	0	0	0	0	0	0	0	0	58.3
5	1	1	-1	1	-1	-1	-1	1	15
6	-1	1	-1	-1	1	1	1	-1	25
7	1	-1	-1	-1	-1	1	1	1	125
8(CP)	0	0	0	0	0	0	0	0	63.8
9	-1	-1	-1	-1	-1	-1	-1	-1	15
10	-1	1	1	-1	-1	-1	1	1	2
11	1	1	1	-1	1	1	-1	1	68.32
12	-1	-1	-1	1	1	1	-1	1	54.6
13	1	-1	1	-1	1	-1	-1	-1	28.6
14	-1	-1	1	1	1	-1	1	1	3
15	-1	1	1	1	-1	1	-1	-1	26.74

Central composite design

A central composite design was chosen to optimize three significant factors that were selected from PB design. Central Composite Design (CCD) combines a two-level factorial design with additional points (star points) and at least one point at the center of the experimental region to obtain properties such as rotatability or orthogonality, in order to fit quadratic polynomials. A factorial design (k^2) is augmented with ($2k$) star points, where k is the number of variables to be optimized, and with a central point, which can be run n times [27]. Center points are usually repeated to get a good estimate of experimental error (pure error). Star points were located at ±α from the centre of the experimental domain, which is $\alpha = \sqrt[4]{2^k}$, to make the experimental design rotatable and orthogonal [27, 28]. Therefore, with four center points and three independent variables totally 18 experiments were involved in the matrix of CCD design. The low (−1), central (0), and high (+1) levels of these variables, as well as the location of their star points are given in Table 4. Table 5 showed design matrix and the three responses, recovery percentage (R), efficiency factor (EF) and volume (µL) of sedimented phase (Vs), for central composite design.

The five-level factorial design of CCD allows an estimate of the response curvature and fitting of a quadratic model to the data. For an experimental design with three factors, This model that is shown in Eq. (1), consisted of three main effects, three two-factor interaction effects and three curvature effects, where b_0 is the intercept and the *b* terms represent those parameters obtained through multiple linear regression.

$$Response = b_0 + b_1F_1 + b_2F_2 + b_3F_3 + b_4F_1\times F_1 + b_5F_2\times F_2 + b_6F_3\times F_3 + b_7F_1\times F_2 + b_8F_1\times F_3 + b_9F_2\times F_3 \quad (1)$$

The second order polynomial with the most reasonable statistics, that is, higher *F*- and *R*-values and low standard error was considered as the satisfactory response surface model to fit the experimental data. The mathematical models were obtained by employing EREGRESS, as Microsoft Excel Add-In software to perform the multivariate regression analysis on the data for each design point. Consequently, a quadratic model was proposed in order to build RSM. To obtain a simple and realistic model the insignificance terms (P>0.05) were eliminated from the model through the "backward elimination" process. Table 4 summarized some characterization of constructed model for efficiency factor, recovery and sedimented phase volume. The adjusted R^2 were well within the acceptable limits of $R^2 \geq 0.9$ and there wasn't large differences between R^2s which represented that the experimental data showed a good fit the second-order polynomial equations. The plots of predicted responses versus calculated ones showed that the residual values were significantly low, for example the regression equation for predictive recovery versus calculated ones were obtained as: $Y=0.9454X+2.8216$ with $R^2=0.9454$. From the constructed models for each response (Table 5) these results could be obtained: dispersion solvent (F_2) affects significantly the enrichment factor by both linear and quadratic variables and extraction solvent (F_1) and sample (F_6) volume only have linear effects in this model. The main interaction variables for EF modeling are: $F_1\times F_2$ and $F_2\times F_6$.

When using recovery as a model response, dispersive solvent volume (F_2) affects the model by both linear and quadratic variables. The extraction solvent (F_1) and sample (F_6) volume only have linear effects in this model. The only main interaction variable for R modeling is $F_2 \times F_6$. For the sedimented phase volume as a response, the obtained model shows no effect of extraction solvent volume (F_1) but dispersive solvent volume has both linear and quadratic effects on the sedimented phase volume (Vs).

Table 4. Independent variables, their levels and symbols for central composite design.

Variable	**Variable levels**			**Star Points (α=1.682)**	
	-1	**0**	**1**	**-α**	**+α**
Volume of extraction solvent (F_1)	200	300	400	100	500
Volume of dispersive solvent (F_2)	1	2	3	0	4
Sample Volume(F_6)	10	15	20	5	25

Table 5. Design matrix and the responses for central composite design.

Run No.	**F1**	**F2**	**F6**	**EF**	**R**	**Vs**
1	-1	1	1	34.67	31.2	180
2	0	0	-1.682	20.89	91.9	220
3	-1	-1	1	121.8	13.4	22
4	0	0	1.682	142.8	38.84	68
5	1	1	1	81.4	70	172
6	1	1	-1	30.41	74.8	246
7	-1	-1	-1	49.15	43.25	88
8	1	-1	1	251.6	47.8	38
9	1	-1	-1	146.1	73.05	50
10	0	-1.682	0	245.5	19.64	12
11	0	0	0	76.47	57.1	112
12	-1	1	-1	15.69	42.05	268
13	0	0	0	78.65	61.87	118
14	0	1.682	0	20.61	43.97	320
15	1.682	0	0	116.1	75.87	98
16	-1.682	0	0	44.67	27.4	92
17	0	0	0	80.28	58.87	110
18	0	0	0	69.14	59	128

Response surface and selection of optimum conditions

The obtained regression models were used to calculate the response surface for each variable separately. Figure 2 showed the RMS plots for recovery and enrichment factor. These figure showed the interaction between two interacting factors when other factors have been kept constant using the constructed models by EREGRESS software. The selection of optimum conditions was possible from the RMS plots. The criteria for optimum value selection were set as follows: recovery near to 100, sedimented phase volume more than 50µL and efficiency factor as high as possible. The conditions that meet these requirements showed in Tables 6 and 7.

Table 6. Some characterizations of constructed models.

Response	R^2	$R^2_{adjustment}$	$R^2_{prediction}$	Regression equation
Enrichment factor (EF)	0.97	0.954	0.879	$EF = 79.73 + 26.9F1 - 57.46F2 + 33.18F6 - 20.66F1\times F2 + 18.32F2\times F2 - 13.52F2\times F6$
Recovery (R)	0.945	0.923	0.874	$R = 58.91 + 15.91F1 + 5.96F2 - 11.71F6 - 9.54F2\times F2 + 4.93F2\times F6$
Sedimented phase volume (Vs)	0.957	0.948	0.924	$Vs = 117.53 + 86.84F2 - 36.29F6 + 16.58F2\times F2$

Table 7. Optimum conditions obtained by RMS for enrichment factor, recovery and sedimented phase volume.

Variable	Optimum values			
	EF	**R**	**Vs**	**Selected optimum value**
Disperser solvent volume F1 (mL)	>2	2.5-3.5	No effect	2
Extraction solvent volume F2 (µL)	<200	200-350	>100	200
sample volume F6(mL)	15-25	5	<15	5

Effect of foreign ions

The effects of common coexisting ions in environmental water samples on the recovery of lead were studied. In these experiments, 5.0mL of solutions contains 0.5 $\mu g\ mL^{-1}$ of lead and different amounts of foreign ions (analyte: foreign ion ratio for heavy metals 1:1, 1:10 ,1:100 and for alkali, alkaline earth and anions 1:100, 1:1000, 1:2500 and 1:5000) were treated according to the recommended procedure. The tolerable concentration of the coexisting ions defined as the largest amount making ±5% variation of the recovery of lead in comparison with the case in which interfering ion was absent. The obtained results are given in Table 8. Alkali and alkaline earth elements do not react with APDC because of its selectivity. However, large amounts of metal ions which react with APDC appreciably reduce the efficiency of lead recovery. (Figure 3)

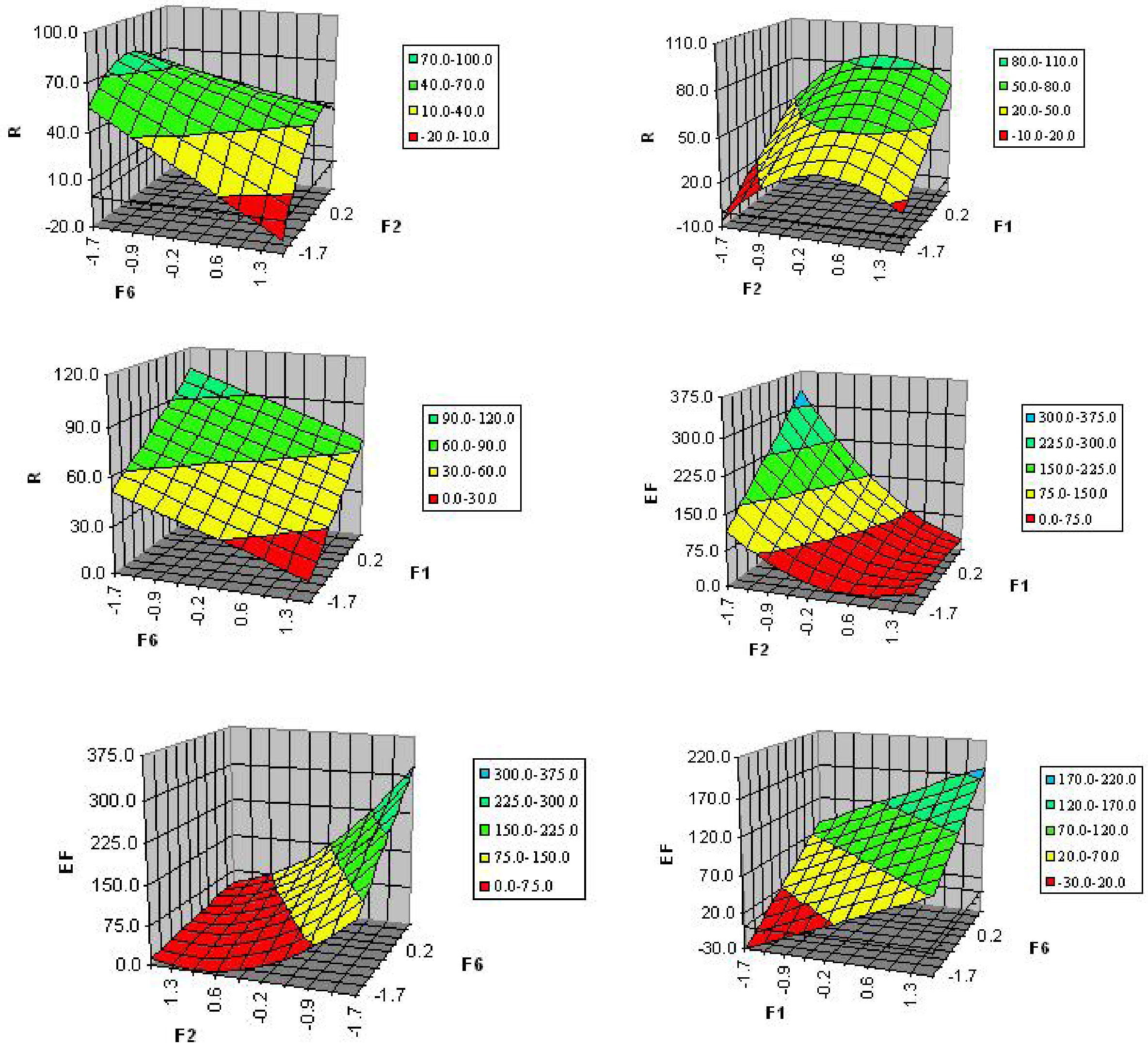

Figure 3. Response surface of recovery (R) and efficiency factor (EF) modeling: volume of extraction solvent (F_1), volume of dispersive solvent (F_2) and sample volume (F_6).

Analysis of real water samples

Tap, mineral, river, dam and sea water samples, used for evaluation of the method, were collected in polypropylene bottles stored at 4°C. Tap water was collected from our laboratory (Tehran, Iran). Dam and river water were collected from Amir Kabir dam and Karaj River (Karaj, Iran). Sea water collocated from Caspian Sea (north of Iran). All of these water samples were firstly filtered through 0.45µm filter and then operated according to DLLME procedure. The real sample analytical results and the recoveries for the spiked samples were shown in Table 9. As can be seen, the recoveries for the spiked real samples ranged from to 93.7% and 104.8% and the R.S.D.s was from 2.6% to 8.5%.

Table 8. Tolerance limits of foreign ions

Foreign ions	Tolerance limits(mgL^{-1})
Si^{+4}, As^{+3}, Co^{+2}, Ni^{+2}, Zn^{+2}, Cr^{+3}, Al^{+3}, Fe^{+3}	1:10
Mn^{+2} , Cu^{+2},	1:100
Li^{+}, Na^{+}, K^{+}	1:5000
Sr^{+2}, Ba^{+2}, Ca^{+2}, Mg^{+2},	1:2500
SO_4^{-2},$H_2PO_4^{-}$, CH_3COO^{-}, Cl^{-}, NO_3^{-} , PO_4^{-3}	1:5000

Table 9. Analysis result of the five kind of environmental water samples at spiked level by the DLLME-ICP-AES.

Sample	Added (μgmL^{-1})	Found (μgmL^{-1})	Recovery (%)
Tap water	0	n.d[b]	
	2	1.95	97
Mineral water	0	n.d	
	2	1.86	93
River water	0	n.d	
	2	2.045	102
Dam water	0	n.d	
	2	2.045	102
Sea water	0	n.d	
	2	2.105	105

[a] n=3 , [b] n.d: not detected

Conclusion

A dispersive liquid- liquid microextraction was used for Pb^{+2} ions from water samples prior to determination by inductively-coupled plasma atomic emission spectrometric technique. Experiments showed that ethanol and chloroform are the most suitable as disperser and as extractor solvents, respectively. To select the most significant variables influence on extraction of Pb^{+2}, PBD was applied and to determine the optimum operating conditions that yield maximum efficiency and recovery, response surface methodologies (RSM) were used. By using central composite design, quadratic and interaction terms between selected variables revealed. Therefore, we were able to see detailed effect of factors on each other and also on the enrichment factor, recovery and sedimented phase volume. This helped us to choose the best experimental conditions for the effective factors more precisely with minimal experimental trials.

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