

Selective separation of some ecotoxic transition metal ions from aqueous solutions using immobilized macrocyclic material containing solid phase extraction system

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journal or publication title	Central European Journal of Chemistry
volume	9
number	6
page range	1019-1026
year	2011-12-01
URL	<a href="http://hdl.handle.net/2297/30138">http://hdl.handle.net/2297/30138</a>

doi: 10.2478/s11532-011-0091-x

1       **Selective Separation of Some Ecotoxic Transition Metal Ions from**  
2               **Aqueous Solutions using Immobilized Macrocyclic Material**  
3                       **Containing Solid Phase Extraction System**

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27 **Abstract**

28 A simple flow-based method was developed for the simultaneous separation of certain  
29 transition metal ions (Co, Ni, Cu, Zn, Cd) from aqueous systems, which ions show ecotoxic  
30 effects when present at elevated concentrations. A silica-gel-bonded macrocycle system,  
31 commonly known as molecular recognition technology (MRT) gel, was used for solid phase  
32 extraction (SPE) of the target analytes. The collection behavior of the MRT-SPE system was  
33 studied based on pH. Fortified deionized water samples containing  $250 \mu\text{g L}^{-1}$  of each of the  
34 elements were treated at the flow rate of  $1 \text{ mL min}^{-1}$ . The collected analytes were then eluted  
35 by  $3 \text{ M HNO}_3$  and analyzed using inductively coupled plasma spectrometry. Detection limits  
36 of the proposed technique were in the range of  $0.004\text{--}0.040 \mu\text{g L}^{-1}$  for the studied metal ions.  
37 The validity of this separation technique was checked with spiked 'real' water samples,  
38 which produced satisfactory recoveries of 96–102%. The non-destructive nature and highly  
39 selective ion-extraction capability of the SPE material are the most important aspects of the  
40 proposed method and they are the main focus of this paper.

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42 **Keywords**

43 Solid phase extraction, Molecular Recognition Technology, non-destructive, selective  
44 separation, aqueous system

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## 52 **1.0 Introduction**

53 The behaviour and effects of transition metal ions (TMIs) in the aquatic environment are  
54 an important issue discussed among the environmental chemists and eco-toxicologists [1-6].  
55 TMIs, at trace level, are readily dissolved and transported in water, and, as being ubiquitous,  
56 can act as a source of environmental pollution [6]. Some TMIs are biologically important;  
57 however, it is difficult to distinguish between their beneficial and harmful effects [7]. TMIs  
58 easily interact with aquatic organisms and they can act as a nutrient in small concentrations,  
59 while the ecotoxic effects may be observed at elevated concentrations [8, 9].

60 Various analytical techniques such as X-ray fluorescence [10], atomic fluorescence  
61 spectrometry [11], atomic absorption spectrophotometry [12, 13], inductively coupled plasma  
62 mass spectroscopy [14], inductively coupled plasma optical emission spectrometry (ICP-  
63 OES) [15, 16] are available for the determination of trace metals, with ICP-based techniques  
64 being the most commonly in use at the present times. Accurate analysis of TMIs in aqueous  
65 samples is difficult due to their complex formation and significant matrices, and because of  
66 their low sensitivity at trace level concentrations [17, 18]. Hence, separation/preconcentration  
67 steps combined with the analytical techniques are suggested to enhance the accuracy of  
68 results and analytical detection limits [7]. Some potential techniques proposed for separation  
69 and preconcentration of TMIs prior to the analytical measurements include co-precipitation  
70 [14, 19], membrane filtration [20], liquid-liquid extraction [21, 22], cloud point extraction  
71 [23-25], micro-extraction [26], and solid-phase extraction [17, 27, 28].

72 Solid phase extraction (SPE) is superior to the conventional extraction techniques [17, 29]  
73 due to its simplicity, rapidity, renewability and eco-safety. Analytical- or process-scale  
74 selective separation using SPE technique requires a material which has (i) highly selective  
75 affinity to the target analyte in the matrix range requiring separation, (ii) fast rate of analyte

76 extraction from the loaded sample solution followed by effortless elution with the suitable  
77 solvent, (iii) repeated usability and (iv) a wide range of accessibility [16, 30-34].

78 A number of SPE materials are available for the selective separation/preconcentration of  
79 TMIs (*e.g.* activated carbon [17], amberlite XAD resins [35], chromosorb resin [36],  
80 amborsorb resin [37], sodium dodecyl sulfate coated alumina [12], polyurethane foam [38],  
81 chitosan [39], molecular recognition technology (MRT) gel [15, 31]). In MRT, macrocycles  
82 covalently attached to the inert silica or polymeric support materials are used as the SPE  
83 material. Here, separation of the target analyte is performed based on the combination of size,  
84 configuration, electronic interaction, charge, wetting, and other factors [40]. The MRT-SPE  
85 materials are commercially available and they offer non-destructive, selective, and fast  
86 separation of the analyte of interest [15, 16, 31-33, 40].

87 In this work, a simple method for separation of Co, Ni, Cu, Zn and Cd from aqueous  
88 samples is proposed using a MRT-SPE system. HNO<sub>3</sub> was used as an eluent to recover the  
89 collected analytes in the MRT-SPE system, and the effluent was subjected to ICP-OES  
90 analysis for metal content evaluation. The parameters including sample pH, flow rate, eluent  
91 volume and concentration were optimized. To the best of our knowledge we report first such  
92 separation from aqueous solution with the application of MRT-SPE system. The technique  
93 has the potential to be used for both, enrichment as well as separation of TMIs from the  
94 natural samples and industrial waste solutions.

## 95 **2.0 Experimental**

### 96 **2.1 Instruments**

97 An SPS 5100 ICP-OES system (SII NanoTechnology Inc., Japan) composed of a radio  
98 frequency generator (40 MHz, 1.2 kW), a one-piece extended torch in the axial view mode,  
99 glass cyclonic spray chamber and sea spray glass concentric nebulizer was used. Argon gas

100 was used to maintain the plasma gas flow, auxiliary gas flow and nebulizer gas flow at 15.0,  
101 1.50 and 0.75 L min<sup>-1</sup>, respectively.

102 An automated computer-controlled robotic system, MetaPREP APS-1 (M&S Instruments,  
103 Japan), was used for sample loading and treatment. A Navi F-52 pH meter (Horiba  
104 Instruments, Japan) and a combination electrode were used for sample pH measurements.

## 105 **2.2 Reagents and materials**

106 Single-element standard stock solutions (1000 mg L<sup>-1</sup>) from Plasma CAL, SCP Science,  
107 Canada, were used to prepare the working standards in the range of mg L<sup>-1</sup> to µg L<sup>-1</sup> *via*  
108 dilution by weight. Ultrapure water (18.3 MΩ cm resistivity), referred to as ultrapure water  
109 hereafter, prepared by an Elix 3/Milli-Q Element system (Nihon Millipore, Japan) was used  
110 throughout the study. Ultrapure reagent grade HNO<sub>3</sub> (PlasmaPURE Plus, SCP Science,  
111 Canada), was diluted with the ultrapure water to the desired concentrations, and used in the  
112 washing and elution steps. Ammonium acetate solution was prepared using acetic acid and  
113 ammonia water, as purchased from Kanto Chemicals, Japan.

114 The ion-selective MRT-SPE material, AnaLig TE-05, was purchased from GL Sciences  
115 Inc., Japan with the following specifications: (a) mesh size – 60 to 100; (b) density – 0.4 g  
116 mL<sup>-1</sup>; (c) operational pH range – up to 10.5; and (d) binding capacity – 0.1 to 0.3 mmol g<sup>-1</sup>.

117 Cations added as NaCl, KCl, CaCl<sub>2</sub>, MgCl<sub>2</sub> and the Na-salt of anions (Cl<sup>-</sup>, NO<sub>3</sub><sup>-</sup>, PO<sub>4</sub><sup>3-</sup>,  
118 SO<sub>4</sub><sup>2-</sup>) (Nacalai Tesque, Japan) were used to study the effect of matrix ions. Working  
119 solutions were prepared in H<sub>2</sub>O matrix with pH maintained at 7. The final solutions were  
120 allowed to equilibrate for 24 h before use.

121 Synthetic multi-element waste solution containing 250 µg L<sup>-1</sup> of several elements,  
122 prepared from the single element metal standard solutions (1000 mg L<sup>-1</sup>) and a multi-element  
123 standard solution XSTC-13 (10 mg L<sup>-1</sup>, Spex CertiPrep Inc., NJ, USA) *via* dilution by weight  
124 and *via* mixing, was used for the recovery test. Fortified samples of the ‘real’ waters (tap and

125 river water), were filtered using the cellulose membrane filter of 0.45  $\mu\text{m}$  pore size (Advantec,  
126 Japan) prior to analysis.

### 127 **2.3 Cleaning**

128 Low-density polyethylene laboratory wares (Nalge, USA) were soaked in an alkaline  
129 detergent (Scat 20X-PF, Nacalai Tesque, Japan) overnight to initiate the process of cleaning.  
130 The further steps included rinsing with ultrapure water followed by soaking in 4 M HCl  
131 overnight, and rinsing again with ultrapure water. The procedure described by Sohrin *et al.*  
132 [41] was followed, in order to clean the perfluoroalkoxy tubes and micropipette tips  
133 (Nichiryo, Japan).

### 134 **2.4 Separation process**

135 A mini-column (3 mL) containing the SPE material was used to evaluate the separation  
136 process in five steps: rinsing, conditioning, collection, washing, and elution (Fig. 1). The  
137 MRT-SPE column was rinsed with 3 M  $\text{HNO}_3$  (10 mL) and ultrapure water (10 mL),  
138 followed by conditioning with the acid or buffer solutions of appropriate pH. Metal ions were  
139 collected from the sample solution after passing through the SPE column. The column was  
140 then washed with 10 mL of ultrapure water. In the next step, the analytes ‘captured’ in the  
141 MRT-SPE column were eluted using 3 M  $\text{HNO}_3$  with subsequent ICP-OES determination.

## 142 **3.0 Results and discussion**

### 143 **3.1 Effect of pH**

144 Collection behaviour of the metal ions (Co, Ni, Cu, Zn or Cd) in the TE-05 MRT-SPE  
145 column was studied as a function of pH (Fig. 2).  $\text{HNO}_3$  (0.001–1 M) and ammonium acetate  
146 solution (0.2 M) were used to adjust the sample pH in the range of 1 to 9. Recovery  
147 efficiencies  $\geq 95\%$  for the studied metal ions were observed at a range of pH or at multiple  
148 pHs: Co (4–8), Ni (6–9), Cu (1–9), Zn (7 and 9), Cd (4–8). However, at pH 7.0, nearly

149 quantitative collection (%) of all the target analytes was observed (Co,  $103\pm 3.56$ ; Ni,  
150  $101\pm 4.46$ ; Cu,  $103\pm 3.66$ ; Zn,  $95.2\pm 3.70$ ; Cd,  $98.4\pm 3.12$ ). Hence, a sample pH at 7 was kept  
151 for further experiments.

### 152 **3.2 Effect of flow rate**

153 Sample loading or elution flow rate have a significant consequence on the performance of  
154 any SPE material during the process of collection or elution. Therefore, at optimum  
155 conditions, the effect of sample loading and elution flow rates on the behaviour of TE-05  
156 column was examined in the range of 1 to 5 and 1 to 4 mL min<sup>-1</sup> respectively (Fig. 3).  
157 Maximum rate (%) of collection (Co,  $101\pm 1.99$ ; Ni,  $100\pm 2.02$ ; Cu,  $101\pm 2.22$ ; Zn,  $102\pm 5.85$ ;  
158 Cd,  $102\pm 2.67$ ) and elution (Co,  $102\pm 1.97$ ; Ni,  $102\pm 4.00$ ; Cu,  $102\pm 2.20$ ; Zn,  $101\pm 2.86$ ; Cd,  
159  $102\pm 2.64$ ) of the target analytes on the MRT-SPE column was observed at the flow rate of 1  
160 mL min<sup>-1</sup>. A gradual decrease in the collection or elution efficiency with the increase in the  
161 flow rates was observed indicating, respectively, the constant collection or regeneration  
162 capability of the MRT-SPE column at the initial period of loading or elution. Based on the  
163 observation, a sample loading or elution flow rate of 1 mL min<sup>-1</sup> was maintained during the  
164 subsequent experiments.

### 165 **3.3 Effect of eluent concentration and volume**

166 A high enrichment factor can be achieved during the separation process, if the eluent  
167 possesses the capacity to recover the analyte with a minimum volume without affecting the  
168 precise determination of the analyte [42]. Fortified aqueous samples, containing 250 µg L<sup>-1</sup>  
169 the target analytes (Co, Ni, Cu, Zn or Cd), were passed through the MRT-SPE column,  
170 followed by elution using 0.5–3 M HNO<sub>3</sub> with succeeding ICP-OES analysis (Fig. 4a). The  
171 maximum recovery (%) of analytes was accomplished at  $\geq 2.0$  M HNO<sub>3</sub>. The requisite eluent  
172 volume for complete elution of the ‘captured’ analytes from the MRT-SPE system was  
173 studied (Fig. 4b). A series of elution experiments with eluent volumes in the range of 2 to 7



174 mL produced discrete patterns in the elution behaviour for different analytes. Maximum  
175 recovery of the target analytes was achieved with the eluent volume of  $\geq 4$  mL. Hence, 4 mL  
176 of 3 M HNO<sub>3</sub> was preferred for the elution steps in the subsequent experiments.

### 177 **3.4 Effect of matrix ions**

178 In order to investigate determination and selective separation of Co, Ni, Cu, Zn, or Cd  
179 ions from their binary mixtures with diverse matrix ions, an aliquot of aqueous solutions (100  
180 mL) containing 250  $\mu\text{g L}^{-1}$  of the target analytes and other ions (Na<sup>+</sup>, K<sup>+</sup>, Ca<sup>2+</sup>, Mg<sup>2+</sup>, Cl<sup>-</sup>,  
181 NO<sub>3</sub><sup>-</sup>, PO<sub>4</sub><sup>3-</sup>, SO<sub>4</sub><sup>2-</sup>) at the molar ratio of 1 to 100 was taken and treated under the optimal  
182 conditions. Satisfactory recovery (%) of the analytes (Co, 101 $\pm$ 3.46; Ni, 100 $\pm$ 4.46; Cu,  
183 102 $\pm$ 4.69; Zn, 95.4 $\pm$ 2.72; Cd, 97.4 $\pm$ 4.12) from aqueous matrix was observed. An error of less  
184 than 5% was considered to be within the range of experimental error. The results indicate that  
185 there is a preferential uptake of the target ions relative to matrix ions, and it is assumed that in  
186 the analysis of aqueous samples, the separation efficiency is not affected by the presence of a  
187 high content of matrix ions.

### 188 **3.5 Analytical characteristics**

189 Aqueous samples fortified with TMIs (Co, Ni, Cu, Zn, Cd) were treated with TE-05  
190 MRT-SPE column, and the concentrations of the target analytes in the treated samples was  
191 measured with ICP-OES. Linear calibration curves were obtained for Co, Ni, Cu, Zn and Cd  
192 concentrations from 1 to 20  $\mu\text{g L}^{-1}$  with the respective correlation coefficients of 0.9785,  
193 0.9755, 0.9955, 0.9914 and 0.9908 under optimum conditions. The method detection limits,  
194 as calculated from three times higher standard deviation ( $n = 15$ ) of the blank, was 0.006,  
195 0.040, 0.006, 0.009 and 0.004  $\mu\text{g L}^{-1}$ . The precision of the method for aqueous standards was  
196 evaluated by analyzing 10 replicates with the analyte concentration of 10  $\mu\text{g L}^{-1}$ , which gave  
197 relative standard deviations of 1.4, 2.2, 1.9, 2.7 and 2.3%, respectively, for Co, Ni, Cu, Zn  
198 and Cd.

### 199 **3.6 Retention capacity and reuse of the SPE column**

200 Retention capacity, which is an indication of the stability of the MRT-SPE column during  
201 the separation process, can be calculated from the analyte concentration and breakthrough  
202 volume (the volume of sample that causes the target analyte to be eluted from the SPE  
203 columns) [43]. Sample solutions spiked with metal ions were passed through the MRT-SPE  
204 column, eluted and subjected to ICP-OES analysis. The retention capacity of the MRT-SPE  
205 at pH 7 was  $0.26\pm 0.08$ – $0.32\pm 0.11$  mmol g<sup>-1</sup>. The regeneration ability of the MRT-SPE  
206 column was investigated, and it was observed that the column could be reused for more than  
207 100 loading and elution cycles without the loss of analytical performance.

### 208 **3.7 Application of the separation process**

#### 209 **3.7.1 Recovery of analytes from synthetic metal-waste solution**

210 Synthetic metal-mixture in aqueous matrix (4 mL) containing 250 µg L<sup>-1</sup> each of 32  
211 different elements (Li, Be, B, Na, Mg, Al, K, Sc, V, Cr, Mn, Fe, Ga, Sr, Zr, Nb, Mo, Rh, Pd,  
212 Ag, Sn, Ba, Hf, Ta, W, Pt, Hg, Tl, Pb, Bi, Th, U) and 5 target analytes was loaded onto MRT-  
213 SPE column followed by elution with 3 M HNO<sub>3</sub> (4 mL). The recoveries (%) of Co, Ni, Cu,  
214 Zn and Cd from the metal-matrix at pH 7 were found to be  $101\pm 2.72$ ,  $100\pm 3.94$ ,  $99.7\pm 4.40$ ,  
215  $96.4\pm 1.83$ , and  $98.2\pm 3.85$ , respectively, after treatment with TE-05 at optimum conditions.

#### 216 **3.7.2 Recovery of analytes from spiked real samples**

217 The proposed separation process was applied for the determination of Co, Ni, Cu, Zn and  
218 Cd in local natural water samples (tap and river water) spiked with known amounts of the  
219 target analytes (Table 1). The recoveries of the target ions from the fortified solutions were in  
220 the range of  $95.8\pm 1.64$  to  $102\pm 3.76\%$ .

### 221 **3.8 Comparison of MRT-SPE with other SPE-systems**

222 Characteristics of the MRT-SPE and some other SPE-systems are compared in Table 2.  
223 The data for other SPE-systems is available in literature [17, 37, 38, 44, 45] and carefully

224 selected based on the number of metals covered during the separation process corresponding  
225 to our study. Most of the SPE systems have been used for column separation of trace metals  
226 at the pH of 6.0–7.5. The advantages of the MRT-SPE system include higher regeneration  
227 ability in comparison with other SPE materials. SPE systems with macrocycles attached onto  
228 solid supports allow selective separation of analytes from matrix facilitating the repeated use  
229 of the macrocycles [46-48]. Hence, superior regeneration ability of the MRT-SPE system is  
230 expected. The initial high cost of synthesis can be amortized over time due to the repeated  
231 usability. The limits of detection achieved by the present method are comparable to those  
232 cited in Table 2. Another advantage of MRT-SPE is the one-step separation process which is  
233 easy to perform and enhances the reproducibility of the separation process

#### 234 **4.0 Conclusions**

235 AnaLig TE-05, an immobilized macrocyclic compound containing SPE system popularly  
236 known as MRT gel, was used for the separation of Co, Ni, Cu, Zn and Cd from aqueous  
237 solutions followed by ICP-OES analysis. Quantitative separation of the target analytes was  
238 performed at the following optimized conditions: a) pH: 7, b) sample loading/elution flow  
239 rate: 1 mL min<sup>-1</sup> and c) eluent: 3 M HNO<sub>3</sub>. Selective separation of the desired ions was  
240 achieved with the MRT-SPE column in the presence of several competing ions. The column  
241 regeneration process is simple and the column can be used for several operations without a  
242 substantial alternation in the analytical performance. Therefore, TE-05 MRT-SPE system  
243 provides an excellent option for the selective separation of Co, Ni, Cu, Zn or Cd ions from  
244 the aqueous matrix with high metal content, or for the separation/preconcentration of the  
245 mentioned ions from natural water systems prior to the analytical determination.

246

247 **Acknowledgment**

248       This research was partially supported by Grants-in-Aid for Scientific Research (K22042)  
249 from Ministry of the Environment, Japan.

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339 Table 1. Determination of analytes in the spiked real water samples ( $n = 5$ )

Analytes	Tap water			River water		
	Added ( $\mu\text{g L}^{-1}$ )	Found ( $\mu\text{g L}^{-1}$ )	Recovery (%)	Added ( $\mu\text{g L}^{-1}$ )	Found ( $\mu\text{g L}^{-1}$ )	Recovery (%)
Co	0	0.11±0.02	–	0	0.10±0.01	–
	100	102±3.43	102±3.38	100	102±3.39	102±3.76
Ni	0	1.33±0.04	–	0	0.95±0.05	–
	100	102±3.81	100±3.78	100	101±3.84	99.9±1.85
Cu	0	1.24±0.13	–	0	0.75±0.03	–
	100	101±2.73	99.4±3.75	100	101±2.69	101±2.05
Zn	0	4.02±0.26	–	0	1.43±0.11	–
	100	102±2.39	98.4±2.52	100	97.2±1.61	95.8±1.64
Cd	0	0.04±0.02	–	0	0.05±0.01	–
	100	96.8±3.31	96.8±4.24	100	98.9±3.17	98.9±3.04

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359 Table 2. Comparative data of the studied ions on different solid phase extraction (SPE)  
 360 systems

Elements	Sample	SPE system <sup>a</sup>	Detector <sup>b</sup>	LOD <sup>c</sup> ( $\mu\text{g L}^{-1}$ )	pH	Reusability (cycle)	Ref.
Co, Ni, Cu, Zn, Cd	Tap and river water	Silica gel/macrocycle	ICP-OES	0.004– 0.040	7	~100	This work
Co, Ni, Cu, Cd, (and Pb, Fe)	Sea water and natural waters	Poly(MAA-co- TMPTMA)	FAAS, GFAAS	0.005– 0.02	7.5	50	[44]
Co, Ni, Cu, Cd, (and Pb, Cr)	Tap water, bottled mineral water	Ambersorb 563/ PAN	FAAS	0.21– 0.67	9	50	[37]
Co, Cu, Cd, Zn, (and Pb, Cr)	Agriculture product, hair, milk, waste and river water samples	SDS-PVC/ BHABDI	FAAS	0.27 – 0.39	7	–	[45]
Co, Ni, Cu, (and Pb)	Natural water samples, leaves of spinach and liver samples	Activated carbon /DHMP	FAAS.	2.9 –8.4	6	–	[17]
Cu, Zn, Cd, (and Pb)	Drinking water	Amberlite XAD-2/ HPAPyr	FAAS	0.9 –3.3	7	17	[28]

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 362 <sup>a</sup> Silica gel/macrocycle: macrocyclic material immobilized on silica gel; poly(MAA-co-TMPTMA): a microsphere polymer gel synthesized  
 363 using methacrylic acid (MAA) as a monomer and trimethylolpropane trimethacrylate (TMPTMA) as a crosslinking agent; ambersorb 563/  
 364 PAN: 1-(2-pyridylazo) 2-naphthol (PAN) impregnated ambersorb 563 resin; SDS-PVC/BHABDI: sodium dodecyl sulfate (SDS)-coated  
 365 poly vinyl chloride (PVC) modified with bis(2-hydroxyacetophenone)-1,4-butanediimine (BHABDI) ligand; activated carbon/DHMP:  
 366 4,6-dihydroxy-2-mercaptopyrimidine (DHMP) loaded on activated carbon; amberlite XAD-2/HPAPyr: amberlite XAD-2 functionalized  
 367 with 4'-(2-hydroxyphenylazo)-3'-methyl-1'-phenyl-2'-pyrazolin-5'-one (HPAPyr).

368 <sup>b</sup> ICP-OES: inductively coupled plasma optical emission spectrometry; FAAS: flame atomic absorption spectrometry; GFAAS: Graphite  
 369 furnace atomic absorption spectrometry

370 <sup>c</sup> LOD: limit of detection  
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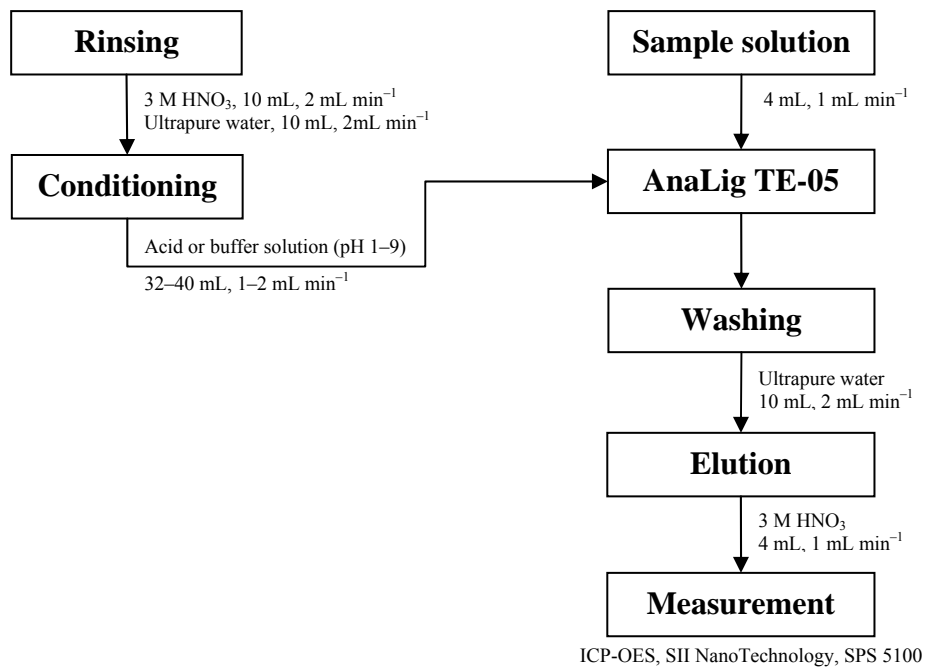


Figure 1: Schematic diagram of the experimental setup

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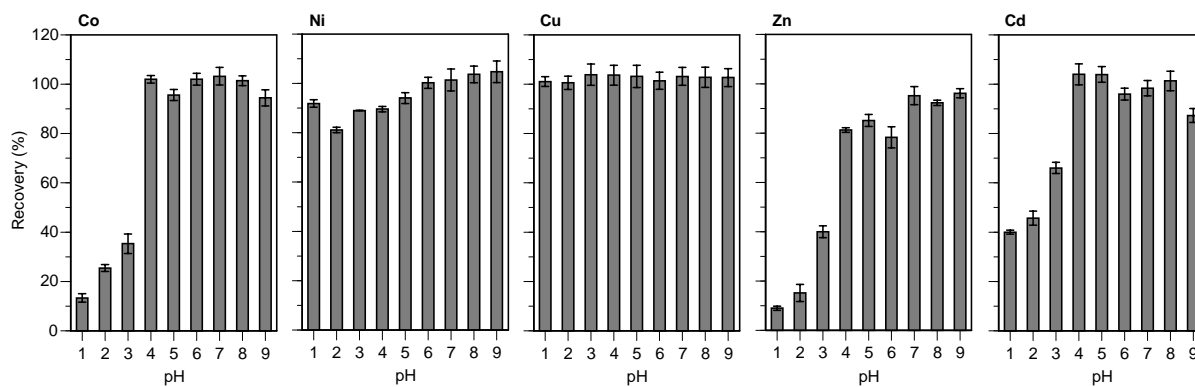
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395 Figure 2: Effect of pH on the collection behavior of the MRT-SPE column. Sample solution:

396  $250 \mu\text{g L}^{-1}$  (Co, Ni, Cu, Zn or Cd), pH: 1–9, volume: 4 mL, loading flow rate:  $1 \text{ mL min}^{-1}$ ,

397 eluent: 3 M  $\text{HNO}_3$ , eluent volume: 4 mL, elution flow rate:  $1 \text{ mL min}^{-1}$  ( $n = 3$ ).

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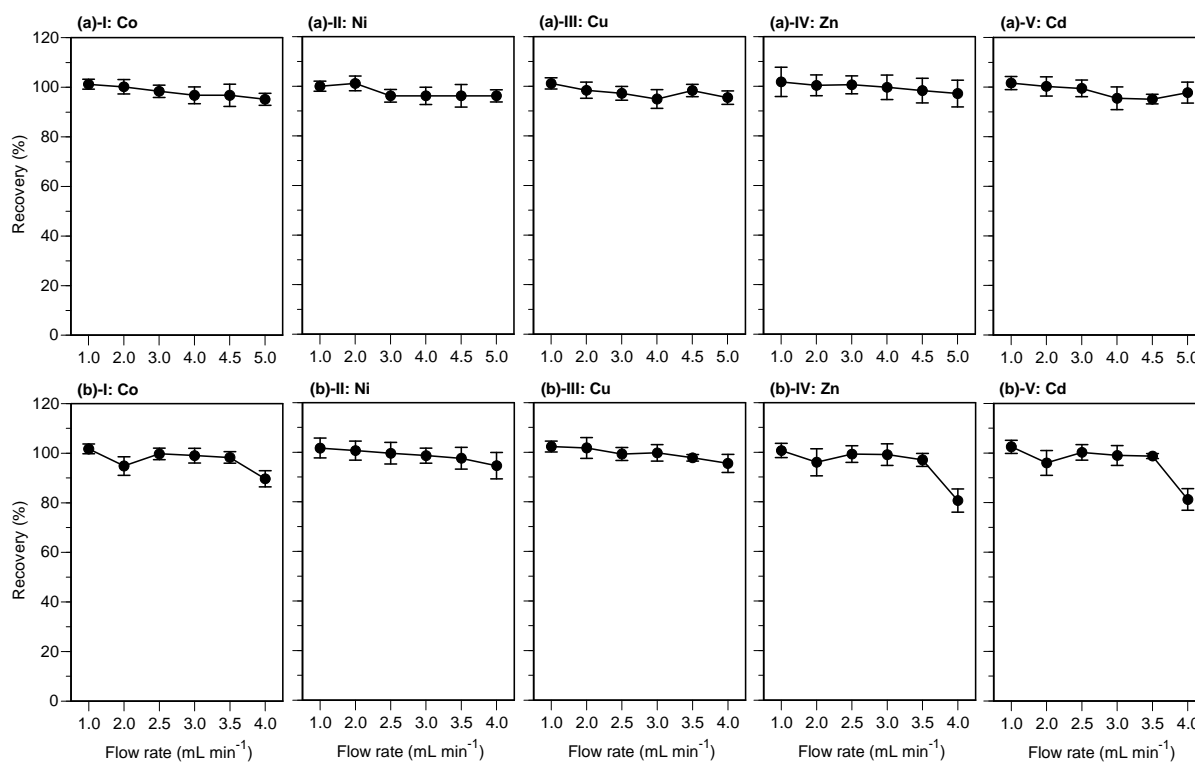
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416 Figure 3: Effect of (a) sample loading and (b) elution flow rates on the collection behavior of

417 the MRT-SPE column. Sample solution: 250  $\mu\text{g L}^{-1}$  (Co, Ni, Cu, Zn or Cd), pH: 7, volume: 4

418 mL, loading flow rate: 1–5 mL min<sup>-1</sup>, eluent: 3 M HNO<sub>3</sub>, eluent volume: 4 mL, elution flow

419 rate: 1–4 mL min<sup>-1</sup> ( $n = 3$ ).

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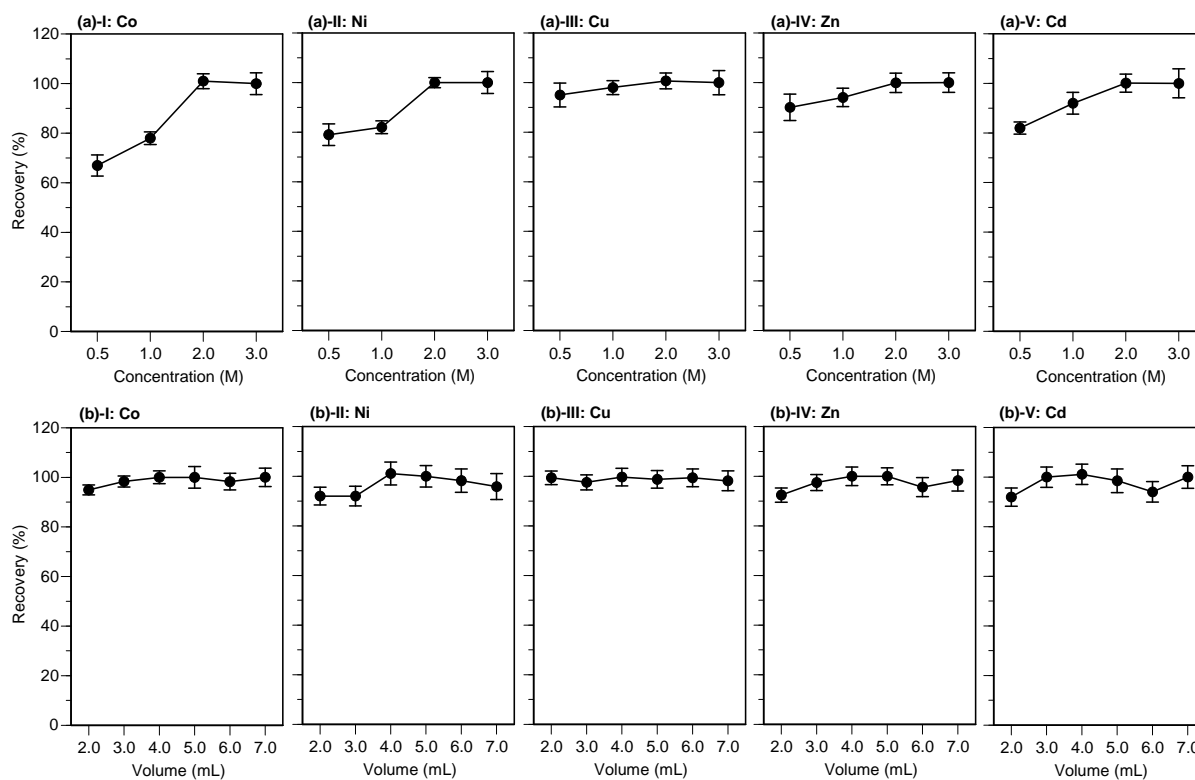
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431 Figure 4: Effect of (a) eluent concentration and (b) eluent volume on the collection behavior  
 432 of the MRT-SPE column. Sample solution:  $250 \mu\text{g L}^{-1}$  (Co, Ni, Cu, Zn or Cd), pH: 7,  
 433 volume: 4 mL, loading flow rate:  $1 \text{ mL min}^{-1}$ , eluent: 0.5–3 M  $\text{HNO}_3$ , eluent volume: 2–7  
 434 mL, elution flow rate:  $1 \text{ mL min}^{-1}$  ( $n = 3$ ).

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