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Citation: Dean, John (2009) Heavy metal bioavailability and bioaccessibility in soil. In: Bioremediation: methods and protocol. Methods in Molecular Biology, 599 . Springer, London, pp. 15-36. ISBN 978-1607614388

Published by: Springer

URL: http://dx.doi.org/10.1007/978-1-60761-439-5_2 <http://dx.doi.org/10.1007/978-1-60761-439-5_2>

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Metadata of the chapter that will be visualized online

ChapterTitle	Heavy Metal Bioavailability and Bioaccessibility in Soil	
Chapter Sub-Title		
Chapter CopyRight - Year	Humana Press, a part of Springer Science+Business Media, LLC 2009 (This will be the copyright line in the final PDF)	
Book Name	Bioremediation	
Corresponding Author	Family Name	Dean
	Particle	
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Abstract	<p>This chapter considers the use of a variety of approaches to assess either the bioavailability or the bioaccessibility of metals in soil. The bioavailability of metals from soils is considered with respect to a series of single-extraction methods, including the use of ethylenediaminetetraacetic acid (EDTA), acetic acid, diethylenetriaminepentaacetic acid (DTPA), ammonium nitrate, calcium chloride and sodium nitrate. Then, a procedure for the recovery of metals using a three-stage sequential extraction protocol is described. Two alternate approaches for assessing the environmental health risk to humans by undertaking in vitro gastrointestinal extraction (also known as the physiologically based extraction test, PBET) are considered. Finally, two acid digestion protocols that allow the pseudo-total metal content of samples to be assessed are provided. In all cases details of how the different approaches can be performed are provided, including the specific reagents required (and their preparation), details of the different extraction and acid digestion protocols to be followed and suitable analytical details to allow the measurement of metals by inductively coupled plasma mass spectrometry (ICP-MS) with/without a collision/reaction cell. A detailed Notes section provides experimental details to guide the reader through some of the practical aspects of the procedures. Finally, some experimental results are provided as evidence of the suitability of the approaches described including single-extraction data, using EDTA and acetic acid, for metals in CRM BCR 700. In addition, in vitro gastrointestinal extraction data are provided for metals in CRM SRM 1570A (spinach leaves). The influence of time on the intestinal fluid phase on the recovery of metals in CRM SRM 1570A (spinach leaves) and CRM INCT-TL-1 (tea leaves) is investigated, as well as the repeatability in terms of recovery of metals from soil over a 3-week period by in vitro gastrointestinal extraction.</p>	
Keywords (separated by '-')	Single-extraction methods - sequential extraction method - physiologically based extraction test (PBET) - in vitro gastrointestinal extraction - inductively coupled plasma mass spectrometry (ICP-MS)	

Chapter 2

Heavy Metal Bioavailability and Bioaccessibility in Soil

John Richard Dean

Abstract

This chapter considers the use of a variety of approaches to assess either the bioavailability or the bioaccessibility of metals in soil. The bioavailability of metals from soils is considered with respect to a series of single-extraction methods, including the use of ethylenediaminetetraacetic acid (EDTA), acetic acid, diethylenetriaminepentaacetic acid (DTPA), ammonium nitrate, calcium chloride and sodium nitrate. Then, a procedure for the recovery of metals using a three-stage sequential extraction protocol is described. Two alternate approaches for assessing the environmental health risk to humans by undertaking in vitro gastrointestinal extraction (also known as the physiologically based extraction test, PBET) are considered. Finally, two acid digestion protocols that allow the pseudo-total metal content of samples to be assessed are provided.

In all cases details of how the different approaches can be performed are provided, including the specific reagents required (and their preparation), details of the different extraction and acid digestion protocols to be followed and suitable analytical details to allow the measurement of metals by inductively coupled plasma mass spectrometry (ICP-MS) with/without a collision/reaction cell. A detailed Notes section provides experimental details to guide the reader through some of the practical aspects of the procedures. Finally, some experimental results are provided as evidence of the suitability of the approaches described including single-extraction data, using EDTA and acetic acid, for metals in CRM BCR 700. In addition, in vitro gastrointestinal extraction data are provided for metals in CRM SRM 1570A (spinach leaves). The influence of time on the intestinal fluid phase on the recovery of metals in CRM SRM 1570A (spinach leaves) and CRM INCT-TL-1 (tea leaves) is investigated, as well as the repeatability in terms of recovery of metals from soil over a 3-week period by in vitro gastrointestinal extraction.

Key words: Single-extraction methods, sequential extraction method, physiologically based extraction test (PBET), in vitro gastrointestinal extraction, inductively coupled plasma mass spectrometry (ICP-MS).

1. Introduction

The release of metals from soil is normally accomplished using heat and concentrated acids (in a process termed acid digestion)

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(1). The aim of this approach is to destroy the soil matrix releasing metals into solution. In reality, depending upon the choice of acid (or acid combination) this may or may not be possible, but the approach is nevertheless used to determine the metal (pseudo)total in the soil matrix. Approaches to assess the metal bioavailability and bioaccessibility are available (2). In the case of metal bioavailability, the approaches are based on the use of selective chemical extractants to liberate the metals from the soil matrix by overcoming specific interactions. These approaches are based on single- or sequential extraction methods, which were originally developed by the Standard, Measurements and Testing Programme (SM & T – formerly BCR) of the European Union (3–5). Single-extraction methods are based on the use of ethylenediaminetetraacetic acid (EDTA), acetic acid or diethylenetriaminepentaacetic acid (DTPA) as well as some other reagents, whereas the sequential extraction method uses specific reagents to assess the exchangeable, reducible and oxidisable fractions of metals in soil. In the case of metal (oral) bioaccessibility, the approach is based on the use of reagents that seek to mimic the human digestive system (2). This method is often described as either in vitro (simulated) gastrointestinal extraction or the physiologically based extraction test (PBET). In each case the use of specific extraction scenarios to provide an estimation of the environmental risk to humans and plants from heavy metal contaminated soil is done.

2. Materials

2.1. Extraction Reagents for Single-Extraction Methods

1. 50 mM ethylenediaminetetraacetic acid (EDTA): In a fume cupboard add 146 \pm 0.05 g of EDTA (free acid) to 800 \pm 20 mL of distilled water (*see Note 1*). To aid dissolution of EDTA, stir in 130 \pm 5 mL of saturated ammonia solution (prepared by bubbling ammonia gas into distilled water). Continue to add the ammonia solution until all the EDTA has dissolved. The resultant solution should be filtered, if necessary, through a filter paper of porosity 1.4–2.0 μ m into a pre-cleaned 10 L polyethylene bottle and then diluted to 9.0 \pm 0.5 L with distilled water. Adjust the pH to 7.00 \pm 0.05 by addition of a few drops of either ammonia or concentrated hydrochloric acid, as appropriate. The solution should then be made up to 10 L with distilled water to obtain an EDTA solution of 50 mM. Analyse a sample of each fresh batch of EDTA solution for its metal impurity content (*see Notes 2 and 3*).

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2. 0.43 M acetic acid: In a fume cupboard add 250 \pm 2 mL of glacial acetic acid (AnalaR or similar) to approximately 5 L of distilled water in a pre-cleaned 10 L polyethylene bottle and make up to 10 L with distilled water. Analyse a sample of each fresh batch of acetic acid solution for its metal impurity content (*see Notes 2 and 3*).
 3. 5 mM diethylenetriaminepentaacetic acid (DTPA): In a fume cupboard dissolve 149.2 g triethanolamine (0.01 M), 19.67 g DTPA (5 mM) and 14.7 g calcium chloride in approximately 200 mL distilled water. Allow the DTPA to dissolve and then dilute to 9 L. Adjust the pH to 7.3 \pm 0.5 with concentrated HCl while stirring and then dilute to 10 L in distilled water. Analyse a sample of each fresh batch of DTPA solution for its metal impurity content (*see Notes 2 and 3*).
 4. 1 M ammonium nitrate (NH_4NO_3): In a fume cupboard dissolve 80.04 g of NH_4NO_3 in water, then make up to 1 L with water. Analyse a sample of each fresh batch of NH_4NO_3 solution for its metal impurity content (*see Notes 2 and 3*).
 5. 0.01 M calcium chloride: In a fume cupboard dissolve 1.470 g of $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ in water, then make up to 1 L with water. Verify that the Ca concentration is 400 \pm 10 mg/L by EDTA titration. Analyse a sample of each fresh batch of CaCl_2 solution for its metal impurity content (*see Notes 2 and 3*).
 6. 0.1 M sodium nitrate (NaNO_3): In a fume cupboard dissolve 8.50 g of NaNO_3 in water, then make up to 1 L with water. Analyse a sample of each fresh batch of NaNO_3 solution for its metal impurity content (*see Notes 2, 3 and 4*).

128 **2.2. Extraction**
129 **Reagents for**
130 **Sequential Extraction**
131 **Method**

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1. Solution A: 0.11 M acetic acid. Add in a fume cupboard 25 \pm 0.1 mL of glacial acetic acid to approximately 0.5 L of water in a 1 L polyethylene bottle and make up to 1 L with water. Take 250 mL of this solution (acetic acid 0.43 M) and dilute to 1 L with water to obtain an acetic acid solution of 0.11 M. Analyse a sample of each fresh batch of solution A for its metal impurity content (*see Note 2*).
 2. Solution B: 0.5 M hydroxylamine hydrochloride or hydroxylammonium chloride. Dissolve 34.75 g of hydroxylamine hydrochloride in 400 mL of water. Transfer to a 1 L volumetric flask and add 25 mL of 2 M HNO_3 (prepared by weighing from a concentration solution) (the pH should be 1.5). Make up to 1 L with water. Prepare this solution on the same day as the extraction is carried out. Analyse a sample of each fresh batch of solution B for its metal impurity content (*see Note 2*).

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**2.3. Extraction
Reagents for In vitro
Gastrointestinal
Extraction:
Approach 1**

3. Solution C: (8.8 M hydrogen peroxide (300 mg/g). Use H_2O_2 as supplied by the manufacturer, i.e. acid-stabilized to pH 2–3. Analyse a sample of each fresh batch of solution C for its metal impurity content (*see Note 2*).
4. Solution D: (1 M ammonium acetate). Dissolve 77.08 g of ammonium acetate in 800 mL of water. Adjust to pH 2 \pm 0.1 with concentrated HNO_3 and make up to 1 L with water. Analyse a sample of each fresh batch of solution D for its metal impurity content (*see Note 2*).

**2.4. Extraction
Reagents for In vitro
Gastrointestinal
Extraction:
Approach 2
Simulated Saliva
Fluid**

1. Gastric solution: 1.25 g pepsin (1 Anson unit/g lactose as diluents), 0.5 g sodium malate, 0.5 g sodium citrate, 420 μL lactic acid and 500 μL acetic acid made up to 1 L with water, adjusted to pH 2.5 with concentrated HCl.
2. Intestinal solution: 52.5 mg bile salts (bovine) and 15 mg pancreatin (pig) added into the sample–gastric solution mixture and the pH adjusted to pH 7.0 with saturated NaHCO_3 .
1. First add 145 mg of α -amylase (bacillus species), 50.0 mg mucin and 15.0 mg uric acid to a 2 L HDPE screw-top bottle.
2. Separately add 896 mg of KCl, 888 mg NaH_2PO_4 , 200 mg KSCN, 570 mg Na_2SO_4 , 298 mg NaCl and 1.80 mL of 1.0 M HCl into a 500 mL volume container and make up to the mark with water (inorganic saliva components).
3. In a second 500 mL volume container, add 200 mg urea and make up to the mark with water (organic saliva components).
4. Then, simultaneously pour 500 mL of inorganic and 500 mL of organic saliva components into the 2 L HDPE screw-top bottle.
5. Shake the entire contents of the screw-top bottle thoroughly.
6. Measure the pH of this solution (gastric-simulated fluid). The pH should be 6.5 ± 0.5 . If necessary, adjust the pH by adding either 1.0 M NaOH or 37% HCl.

**2.5. Simulated
Gastric Fluid**

1. First add 1000 mg of bovine serum albumin, 3000 mg mucin and 1000 mg pepsin to a 2 L HDPE screw-top bottle.
2. Separately add 824 mg of KCl, 266 mg NaH_2PO_4 , 400 mg CaCl_2 , 306 mg NH_4Cl , 2752 mg NaCl and 8.30 mL of 37% HCl into a 500 mL volume container and make up to the mark with water (inorganic gastric components).
3. In a second 500 mL volume container, add 650 mg glucose, 20.0 mg glucuronic acid, 85.0 mg urea and

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193 330 mg glucosaminehydrochloride and make up to the mark
194 with water (organic gastric components).

- 195 4. Then, simultaneously pour 500 mL of inorganic and
- 196 500 mL of organic components into the 2 L HDPE screw-
- 197 top bottle.
- 198 5. Shake the entire contents of the screw-top bottle thoroughly.
- 199 6. Measure the pH of this solution (gastric-simulated fluid).
- 200 The pH should be within the range 0.9–1.0. If necessary,
- 201 adjust the pH to this range (0.9–1.0) by adding either 1.0 M
- 202 NaOH or 37% HCl.
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- 204 7. Check that the combination of mixed saliva fluid (1 mL) and
- 205 gastric fluid (1.5 mL) is in the pH 1.2–1.4. If the combined
- 206 mixture is not within this range, it is necessary to adjust the
- 207 pH of the gastric fluid by adding either 1.0 M NaOH or 37%
- 208 HCl.
- 209 8. Re-check that the combination of mixed saliva fluid (1 mL)
- 210 and gastric fluid (1.5 mL) is in the pH 1.2–1.4.

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212 **2.6. Simulated**

213 **Duodenal Fluid**

- 214 1. First add 200 mg of CaCl_2 , 1000 mg bovine serum albu-
- 215 min, 3000 mg pancreatin and 500 mg lipase to a 2 L HDPE
- 216 screw-top bottle.
- 217 2. Separately add 564 mg of KCl, 80 mg KH_2PO_4 , 50.0 mg
- 218 MgCl_2 , 5607 mg NaHCO_3 , 7012 mg NaCl and 180 μL of
- 219 37% HCl into a 500 mL volume container and make up to
- 220 the mark with water (inorganic duodenal components).
- 221 3. In a second 500 mL volume container, add 100 mg urea and
- 222 make up to the mark with water (organic duodenal compo-
- 223 nents).
- 224 4. Then, simultaneously pour 500 mL of inorganic and
- 225 500 mL of organic duodenal components into the 2 L
- 226 HDPE screw-top bottle.
- 227 5. Shake the entire contents of the screw-top bottle thoroughly.
- 228 6. Measure the pH of this solution (simulated duodenal fluid).
- 229 The pH should be within the range 7.4 ± 0.2 . If necessary,
- 230 adjust the pH of the duodenal fluid by adding either 1.0 M
- 231 NaOH or 37% HCl.

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234 **2.7. Simulated Bile**

235 **Fluid**

- 236 1. First add 222 mg of CaCl_2 , 1800 mg bovine serum albumin
- 237 and 6000 mg bile to a 2 L HDPE screw-top bottle.
- 238 2. Separately add 376 mg of KCl, 5785 mg NaHCO_3 ,
- 239 5259 mg NaCl and 180 μL of 37% HCl into a 500 mL
- 240 volume container and make up to the mark with water (inor-
- ganic bile components).

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- 241 3. Into a second 500 mL volume container, add 250 mg urea
 242 and make up to the mark with water (organic bile compo-
 243 nents).
 244 4. Then, simultaneously pour 500 mL of inorganic and 500
 245 mL of organic bile components into the 2 L HDPE screw-
 246 top bottle.
 247 5. Shake the entire contents of the screw-top bottle thoroughly.
 248 6. Allow the solution to stand for approximately 1 h, at room
 249 temperature, to allow for complete dissolution of solid
 250 reagents.
 251 7. Measure the pH of this solution (simulated bile fluid). The
 252 pH should be within the range 8.0 ± 0.2 . If necessary, adjust
 253 the pH of the duodenal fluid by adding either 1.0 M NaOH
 254 or 37% HCl.
 255 8. Check that the combination of saliva fluid (1.0 mL), gastric
 256 fluid (1.5 mL), 3.0 mL duodenal fluid and 1.0 mL bile fluid
 257 is in the pH 6.3 ± 0.5 . If the combined mixture is not within
 258 this range, it is necessary to adjust the pH of the duodenal
 259 fluid by adding either 1.0 M NaOH or 37% HCl.
 260 9. Re-check that the combination of saliva fluid (1.0 mL), gas-
 261 tric fluid (1.5 mL), 3.0 mL duodenal fluid and 1.0 mL bile
 262 fluid is in the pH 6.3 ± 0.5 .
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265 **2.8. Instrumentation**

266 **for Metal Analysis**

- 267 1. All metal measurements were made using an inductively
 268 coupled plasma mass spectrometer (ICP-MS, XSeries II,
 269 Thermo Electron Corporation, Cheshire, UK).
 270 2. A multi-element standard is used for K, Ca, Mg, Na, Cr, Mn,
 271 Fe, Ni, Cu, Zn, Mo, Cd and Pb and internal standard solu-
 272 tions for Sc, In and Tb (SPEXCertiPrep, Middlesex, UK).
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275 **3. Methods**

276 **3.1. Chemical-**

277 **Selective Extraction**

278 **for Single-Extraction**

279 **Methods**

280 Chemical-selective extractions of the soil are carried out in order
 281 to assess the metal bioavailability. The main procedures identified
 282 for the extraction of metals using single-extraction methods are
 283 based on the use of ethylenediaminetetraacetic acid, acetic acid or
 284 diethylenetriaminepentaacetic acid. However, other reagents are
 285 also used and include the use of ammonium nitrate, calcium chlo-
 286 ride and sodium nitrate. The extraction protocols, using EDTA,
 287 CH_3COOH and CaCl_2 , used are based on those developed by the
 288 Standard, Measurements and Testing Program (formerly BCR) of
 the European Community (3–5) and subsequently re-evaluated
 for EDTA and acetic acid (6).

289 **3.1.1. Ethylenedi-**
290 **aminetetraacetic Acid**
291 **Extraction**

1. 2 g of soil sample is weighed into a 50 mL Sarstedt extraction tube and 20 mL of 0.05 M EDTA (pH 7.0) is added (*see Note 5*).
2. The mixture is shaken in an end-over-end shaker at 30 rpm for 1 h at ambient temperature ($20 \pm 2^\circ\text{C}$) (*see Note 6*).
3. Then centrifuge the mixture for 10 min at 3000*g*.
4. Remove the supernatant with a pipette and store in a polyethylene bottle at 4°C .
5. Prior to analysis, re-homogenise the sample by manually shaking for 5 min.
6. Analyse by ICP-MS (*see Notes 10 and 11*).

1. Example results for the EDTA extraction of nine elements from a certified reference material (BCR 700) are shown in **Table 2.1**.

307 **Table 2.1**
308 **Example results for selected single-extraction protocols**

Element	EDTA extraction		CH ₃ COOH extraction	
	CRM organic-rich soil (BCR 700) (mg/kg)	Concentrations (mg/kg) Mean \pm SD, <i>n</i> = 6	CRM organic-rich soil (BCR 700) (mg/kg)	Concentrations (mg/kg) Mean \pm SD, <i>n</i> = 6
Cr	10.1 \pm 0.9	9.2 \pm 0.2	19.0 \pm 1.1	20.5 \pm 0.7
Mn	na	146 \pm 6	na	266 \pm 19
Fe	na	1224 \pm 95	na	33.0 \pm 1.8
Ni	53.2 \pm 2.8	51.5 \pm 1.0	99.0 \pm 5.1	102.8 \pm 2.6
Cu	89.4 \pm 2.8	91.9 \pm 1.3	36.3 \pm 1.6	37.3 \pm 2.6
Zn	510 \pm 17	455 \pm 5	719 \pm 24	715.7 \pm 55.5
Mo	na	1.10 \pm 0.08	na	0.06 \pm 0.01
Cd	65.2 \pm 3.5	65.7 \pm 5.1	67.5 \pm 2.8	67.1 \pm 2.5
Pb	103 \pm 5	101.9 \pm 0.9	4.85 \pm 0.38	4.82 \pm 0.44

325 na = not available

328 **3.1.2. Acetic Acid**
329 **Extraction**

1. 1 g of soil sample is weighed into a 50 mL Sarstedt extraction tube and 40 mL of 0.43 M CH₃COOH is added (*see Note 5*).
2. The mixture is shaken in an end-over-end shaker at 30 rpm for 16 h at ambient temperature ($20 \pm 2^\circ\text{C}$) (*see Note 6*).
3. Then centrifuge the mixture for 10 min at 3000*g*.
4. Remove the supernatant with a pipette and store in a polyethylene bottle at 4°C .

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5. Prior to analysis, re-homogenise the sample by manually shaking for 5 min.

6. Analyse by ICP-MS (*see Notes 10 and 11*).

Example results for the acetic acid extraction of nine elements from a certified reference material (BCR 700) are shown in **Table 2.1**.

3.1.3. Diethylenetri-aminepentaacetic Acid Extraction

1. 2 g of soil sample is weighed into a 50 mL Sarstedt extraction tube and 4 mL of 0.005 M DTPA is added (*see Note 5*).

2. The mixture is shaken in an end-over-end shaker at 30 rpm for 2 h at ambient temperature ($20 \pm 2^\circ\text{C}$) (*see Note 6*).

3. Then centrifuge the mixture for 10 min at 3000g.

4. Remove the supernatant with a pipette and store in a polyethylene bottle at 4°C .

5. Prior to analysis, re-homogenise the sample by manually shaking for 5 min.

6. Analyse by ICP-MS (*see Notes 10 and 11*).

3.1.4. Calcium Chloride Extraction

1. 2 g of soil sample is weighed into a 50 mL Sarstedt extraction tube and 20 mL of 0.01 M CaCl_2 is added (*see Note 5*).

2. The mixture is shaken in an end-over-end shaker at 30 rpm for 3 h at ambient temperature ($20 \pm 2^\circ\text{C}$) (*see Note 6*).

3. Decant 12 mL into a centrifuge tube and centrifuge for 10 min at 3000g.

4. Analyse extracts immediately by ICP-MS (*see Notes 10 and 11*).

3.1.5. Ammonium Nitrate

1. 2 g of soil sample is weighed into a 50 mL Sarstedt extraction tube and 5 mL of 1.0 M NH_4NO_3 is added (*see Note 5*).

2. The mixture is shaken in an end-over-end shaker at 50–60 rpm for 2 h at ambient temperature ($20 \pm 2^\circ\text{C}$) (*see Note 6*).

3. Then, pass the supernatant through an acid-washed filter paper into a 50 mL polyethylene bottle (discard the first 5 mL of the filtrate). Stabilise by adding 1 mL of concentrated HNO_3 .

4. If solids remain, centrifuge or filter through a $0.45 \mu\text{m}$ membrane filter.

5. Analyse extracts immediately by ICP-MS (*see Notes 10 and 11*).

3.1.6. Sodium Nitrate Extraction

1. 2 g of soil sample is weighed into a 50 mL Sarstedt extraction tube and 5 mL of 0.1 M NaNO_3 is added (*see Note 5*).

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2. The mixture is shaken in an end-over-end shaker at 120 rpm for 2 h at ambient temperature ($20 \pm 2^\circ\text{C}$) (*see Note 6*).
3. Then centrifuge the mixture for 10 min at 4000*g*.
4. Remove the supernatant with a syringe and filter through a 0.45 μm membrane filter into a 50 mL polyethylene bottle. Add 2 mL of concentrated HNO_3 to a 50 mL volumetric flask and make up to volume with the filtered extract.
5. Analyse extracts immediately by ICP-MS (*see Notes 10 and 11*).

3.2. Chemical- Selective Extraction for Sequential Extraction Method

The procedure adopted for the sequential extraction of metals from soil/sediments is based on three distinct stages (6). In stage 1 (exchangeable fraction), the metals released are representative of those that are the most bioavailable (and hence most mobile). They include those metals that are weakly absorbed on the sediment/soil surface by relatively weak electrostatic interaction, metals that can be released by ion exchange processes or metals that can be co-precipitated with carbonates present in many sediments/soils. Any changes in the ionic composition, influencing adsorption–desorption reactions, or lowering of pH could cause mobilisation of metals from this fraction. In stage 2 (reducible fraction), the metals bound to iron/manganese oxides are identified; they are therefore unstable under reduction conditions. Changes in the redox potential (E_h) could induce the dissolution of these oxides, leading to their release from the soil/sediment. Finally, in stage 3 (oxidisable fraction), those metals bound to organic matter within the sediment/soil matrix are released into solution. The residual fraction is then acid-digested (*see Section 6*).

3.2.1. Stage 1 Extraction

1. 1 g of soil sample is weighed into a 80–100 mL PTFE centrifuge tube and 40 mL of acetic acid (0.11 M) – Solution A – is added (*see Note 5*).
2. The mixture is shaken in an end-over-end shaker at 30 rpm for 16 h at ambient temperature ($22 \pm 5^\circ\text{C}$) (*see Notes 6 and 7*).
3. Centrifuge at 3000*g* for 20 min.
4. Remove the supernatant with a pipette and store in a polyethylene bottle at 4°C .
5. Analyse extracts by ICP-MS (*see Notes 10 and 11*).
6. Wash the residue with 20 mL of water by shaking for 15 min.
7. Centrifuge the residue for 20 min at 3000*g* and discard the supernatant. Take care not to lose any of the solid residue.

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3.2.2. Stage 2 Extraction

8. Break the “cake” formed during centrifugation prior to stage 2.
1. Add 40 mL of hydroxylammonium chloride (0.1 M, adjusted to pH 2 with nitric acid) – Solution B – to the residue from stage 1.
2. The mixture is shaken in an end-over-end shaker at 30 rpm for 16 h at ambient temperature ($22 \pm 5^\circ\text{C}$) (*see Note 6*).
3. Centrifuge at $3000g$ for 20 min.
4. Remove the supernatant with a pipette and store in a polyethylene bottle at 4°C .
5. Analyse extracts by ICP-MS (*see Notes 10 and 11*).
6. Wash the residue with 20 mL of water by shaking for 15 min.
7. Centrifuge the residue for 20 min at $3000g$ and discard the supernatant. Take care not to lose any of the solid residue.
8. Break the “cake” formed during centrifugation prior to stage 3.

3.2.3. Stage 3 Extraction

1. Add carefully, to avoid losses due to any violent reaction, 10 mL of hydrogen peroxide (8.8 M) – Solution C – to the residue from stage 2.
2. Allow the sample to digest for 1 h with occasional manual stirring. Ensure the container is covered with a watch glass (or similar).
3. Continue the digestion by heating the sample to $85 \pm 2^\circ\text{C}$, with occasional manual stirring for the first 30 min, for 1 h in a water bath or similar.
4. Reduce the volume of liquid to 2–3 mL by further heating, after removal of the watch glass.
5. Add a further 10 mL of hydrogen peroxide (Solution C) and heat to $85 \pm 2^\circ\text{C}$ for 1 h in a water bath (with occasional manual stirring for the first 30 min).
6. Remove the watch glass and reduce the volume of liquid to approximately 1 mL by further heating.
7. Add 50 mL of ammonium acetate (1.0 M) – Solution D – to the cooled, moist residue.
8. The mixture is shaken in an end-over-end shaker at 30 rpm for 16 h at ambient temperature ($20 \pm 5^\circ\text{C}$).
9. Centrifuge at $3000g$ for 20 min.
10. Remove the supernatant with a pipette and store in a polyethylene bottle at 4°C .
11. Analyse extracts by ICP-MS (*see Notes 10 and 11*).

481 **3.3. Physiologically**
 482 **Based Extraction**
 483 **Test or In vitro**
 484 **Gastrointestinal**
 485 **Extraction**
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In vitro gastrointestinal extraction consists of two sequential processes, a gastric and an intestinal digestion, each one carried out employing simulated human conditions (enzymes, pH and temperature) (2). Several distinct approaches for performing in vitro gastrointestinal extraction are available (7, 8); however, two are considered in this chapter.

488 **3.3.1. Approach 1:**
 489 **Gastric Extraction**
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1. 0.3 g (accurately weighed) of sample is placed into a 50 mL screw-cap Sarstedt tube and treated with 30 mL of gastric juice.
2. The mixture is then shaken at 100 rpm in a thermostatic water bath maintained at 37°C.
3. After 1 h, the solution is centrifuged at 3000 rpm for 10 min and a 5 mL aliquot is removed and filtered through 0.45 µm filter disk.
4. The extracts are analysed by ICP-MS (*see Notes 10 and 11*).
5. 5.0 mL of the original gastric solution is then backflushed through the filter into the sample tube to retain the original solid:solution ratio, i.e. 0.3:30 g/mL.

502 **3.3.2. Approach 1:**
 503 **Intestinal Extraction**
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1. Intestinal juice (52.5 mg bile salts and 15 mg pancreatin) is added into the sample tube and the mixture is adjusted to pH 7.0 with saturated NaHCO₃.
2. The sample is shaken at 100 rpm in a thermostatic water bath maintained at 37°C for a further 2 h.
3. A 5.0 mL aliquot is removed and filtered and analysed by ICP-MS.
4. After an additional 2 h, a second 5.0 mL extract aliquot is removed, filtered and analysed by ICP-MS (*see Notes 10 and 11*).
5. The second intestinal aliquot is used to check that the small intestinal equilibrium has been reached (9).

Example results for the in vitro gastrointestinal extraction of nine elements from two certified reference materials (INCT-TL-1 and SRM 1570a) are shown in **Table 2.2**. Data indicating that the additional 2 h equilibration period (*see Section 3.3.2*, Step 4) had no significance at the 95% confidence interval are shown in **Table 2.3** for the two certified reference materials. The repeatability of the in vitro gastrointestinal extraction for the recovery of eight elements from a contaminated soil digest on three separate occasions is shown in **Table 2.4**.

3.3.3. Approach 2:
"Stomach" Extraction

1. 0.6 g (accurately weighed) of sample is placed into a 50 mL screw-cap Sarstedt tube and treated with 9 mL of simulated saliva fluid (*see Note 12*).

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Table 2.2
Example results for in vitro gastrointestinal extraction using approach 1
(A)

Element	Certified values of tea leaves (INCT-TL-1) (mg/kg)	Concentration (mg/kg)						Σ Total stages Mean \pm SD (n = 3)
		Gastric stage		Intestinal stage		Residual stage		
		Mean \pm SD (n = 3)	%	Mean \pm SD (n = 3)	%	Mean \pm SD (n = 3)	%	
Cr	1.91 \pm 0.22	0.67 \pm 0.13	32.57	0.73 \pm 0.09	35.73	0.65 \pm 0.09	31.70	2.04 \pm 0.11
Mn	1570 \pm 110	998 \pm 298	58	356 \pm 231	21	360 \pm 32	21	1714 \pm 105
Fe	(432)	1 \pm 1	0.2	6 \pm 2	1.5	429 \pm 46	98.3	437 \pm 43
Ni	6.12 \pm 0.52	2.68 \pm 0.57	39.82	2.43 \pm 0.24	36.05	1.63 \pm 0.46	24.13	6.74 \pm 0.43
Cu	20.4 \pm 1.5	3.7 \pm 1.0	17.3	7.2 \pm 0.5	33.3	10.7 \pm 1.1	49.5	21.7 \pm 0.4
Zn	34.7 \pm 2.7	17.0 \pm 2.8	40.8	10.9 \pm 1.3	26.2	13.7 \pm 2.6	32.9	41.7 \pm 4.9
Mo	Na	0.005 \pm 0.003	6.13	0.024 \pm 0.005	27.20	0.058 \pm 0.002	66.67	0.087 \pm 0.003
Cd	0.030 \pm 0.004	0.016 \pm 0.013	41.69	0.004 \pm 0.003	9.91	0.018 \pm 0.020	48.40	0.038 \pm 0.012
Pb	1.78 \pm 0.24	0.13 \pm 0.02	7.45	0.20 \pm 0.02	11.51	1.40 \pm 0.01	81.04	1.73 \pm 0.05

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Element	Certified values of spinach leaves (SRM 1570a) (mg/kg)		Concentration (mg/kg)				Σ Total stages	
	Mean \pm SD	Gastric stage		Intestinal stage		Residual stage		
		Mean \pm SD	Mean \pm SD ($n = 3$)	%	Mean \pm SD ($n = 3$)	%	Mean \pm SD ($n = 3$)	%
Cr	na	0.15 \pm 0.02	9.64	0.29 \pm 0.07	18.54	1.11 \pm 0.07	71.82	1.54 \pm 0.08
Mn	75.9 \pm 1.9	39.0 \pm 0.6	47.0	31.0 \pm 4.9	37.3	13.0 \pm 2.0	15.7	83.0 \pm 4.0
Fe	NA	38 \pm 3	20.2	63 \pm 3	33.3	88 \pm 5	46.5	189 \pm 6
Ni	2.14 \pm 0.10	0.87 \pm 0.06	42.13	0.73 \pm 0.09	35.53	0.46 \pm 0.18	22.33	2.06 \pm 0.20
Cu	12.2 \pm 0.6	6.4 \pm 0.1	44.7	5.7 \pm 0.4	40.4	2.1 \pm 0.5	14.9	14.2 \pm 0.4
Zn	82 \pm 3	52 \pm 2	57.1	30 \pm 1	32.2	10 \pm 0.4	10.7	92 \pm 3
Mo	na	0.206 \pm 0.041	37.07	0.312 \pm 0.052	55.99	0.039 \pm 0.011	6.94	0.557 \pm 0.086
Cd	2.89 \pm 0.07	1.02 \pm 0.19	37.44	0.64 \pm 0.11	23.42	1.07 \pm 0.08	39.14	2.73 \pm 0.37
Pb	na	0.120 \pm 0.068	30.68	0.110 \pm 0.075	28.15	0.161 \pm 0.083	41.17	0.392 \pm 0.076

na = not available

Table 2.2 (continued)
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Table 2.3
Example results for the extraction equilibrium of the intestinal fluid phase

Element	Bioaccessible metals (mg/kg) – tea leaves (INCT-TL-1)						Bioaccessible metals (mg/kg) – spinach leaves (SRM 1570a)					
	Intestinal stage IIA		Intestinal stage IIB		<i>t</i> -stat	<i>P</i> -value	Intestinal stage IIA		Intestinal stage IIB		<i>t</i> -stat	<i>P</i> -value
	Mean (<i>n</i> = 3)	SD	Mean (<i>n</i> = 3)	SD			Mean (<i>n</i> = 3)	SD	Mean (<i>n</i> = 3)	SD		
Cr	0.730	0.093	0.760	0.100	-0.512	0.660	0.286	0.073	0.302	0.098	-0.794	0.511
Mn	356.020	230.635	324.751	201.412	1.737	0.225	30.972	4.873	30.086	3.757	0.946	0.444
Fe	6.415	1.901	5.990	1.912	5.899*	0.028*	62.857	3.005	59.936	1.364	2.752	0.111
Ni	2.429	0.236	2.208	0.101	1.247	0.339	0.733	0.091	0.720	0.117	0.873	0.475
Cu	7.212	0.465	7.147	0.985	0.162	0.886	5.741	0.431	5.923	0.601	-0.773	0.520
Zn	10.934	1.264	10.832	1.304	0.191	0.866	28.621	1.011	28.731	2.432	-0.109	0.923
Mo	0.024	0.005	0.020	0.003	3.417	0.076	0.312	0.052	0.278	0.059	3.687	0.066
Cd	0.004	0.003	0.003	0.001	1.153	0.368	0.639	0.115	0.603	0.131	2.705	0.114
Pb	0.199	0.024	0.215	0.038	-1.019	0.415	0.110	0.075	0.115	0.078	-1.982	0.186

Note: *t*-critical (two-tail) is 4.303 and *P*-values are reported at 5% significance level.

*1% significance level giving *t*-critical = 9.925.

Intestinal stage IIA refers to **Section 3.3.2**, Step 1–3, while intestinal stage IIB refers to **Section 3.3.2**, Step 4.

Element	Aqua regia digest of soil (mg/kg)	Concentration (mg/kg)						Σ Total stages Mean \pm SD (n = 3)
		Gastric stage		Intestinal stage		Residual stage		
		Mean \pm SD (n = 3)	%	Mean \pm SD (n = 3)	%	Mean \pm SD (n = 3)	%	
Cr	130.2 \pm 4.8	7.46 \pm 0.15	5.2	9.89 \pm 0.32	6.8	127.0 \pm 12.9	88.0	144.3
Mn	4980 \pm 207	2269 \pm 99	46.2	1349 \pm 104	27.5	1293 \pm 23	26.3	4911
Ni	69.1 \pm 3.3	7.80 \pm 0.22	11.9	5.80 \pm 0.21	8.9	51.8 \pm 1.5	79.2	65.4
Cu	25.0 \pm 2.8	1.78 \pm 0.03	8.9	5.25 \pm 0.09	26.5	12.8 \pm 0.3	64.6	19.8
Zn	133.4 \pm 3.8	19.8 \pm 1.4	14.2	4.86 \pm 0.11	3.5	114.6 \pm 4.7	82.3	139.2
Mo	4.2 \pm 0.4	0.43 \pm 0.01	12.3	0.62 \pm 0.01	17.7	2.45 \pm 0.02	70.0	3.5
Cd	0.91 \pm 0.02	0.14 \pm 0.00	17.1	0.04 \pm 0.01	4.9	0.64 \pm 0.01	78.0	0.82
Pb	59.8 \pm 0.4	0.67 \pm 0.06	1.6	0.50 \pm 0.03	1.2	41.8 \pm 0.8	97.2	43.0

(continued)

Table 2.4
Example results for in vitro gastrointestinal extraction using approach 1
(a) Data from week 1

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Element	Aqua regia digest of soil (mg/kg) Mean ± SD	Gastric stage		Concentration (mg/kg)				Σ Total stages Mean ± SD (n = 3)
		Mean ± SD (n = 3)	%	Intestinal stage		Residual stage		
				Mean ± SD (n = 3)	%	Mean ± SD (n = 3)	%	
Cr	130.2 ± 4.8	6.31 ± 0.13	4.5	10.78 ± 0.28	7.7	122.9 ± 8.9	87.8	139.9
Mn	4980 ± 207	1554.3 ± 50.2	29.6	802.0 ± 18.2	15.2	2900 ± 70	55.2	5256
Ni	69.1 ± 3.3	6.20 ± 0.40	11.1	7.59 ± 0.37	13.7	41.8 ± 3.1	75.2	55.6
Cu	25.0 ± 2.8	1.62 ± 0.05	6.3	6.00 ± 0.21	23.2	18.2 ± 1.1	70.5	25.8
Zn	133.4 ± 3.8	24.4 ± 4.9	19.0	4.44 ± 0.23	3.5	99.6 ± 3.6	77.5	128.4
Mo	4.2 ± 0.4	0.51 ± 0.01	10.5	0.76 ± 0.03	15.6	3.59 ± 0.06	73.9	4.9
Cd	0.91 ± 0.02	0.13 ± 0.01	14.3	0.06 ± 0.06	6.6	0.72 ± 0.01	79.1	0.9
Pb	59.8 ± 0.4	0.29 ± 0.03	0.5	0.62 ± 0.06	1.1	55.7 ± 1.5	98.4	56.6

(continued)

Table 2.4 (continued)
(b) Data from week 2

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Element	Aqua regia digest of soil (mg/kg) Mean ± SD	Concentration (mg/kg)						Σ Total stages Mean ± SD (n = 3)
		Gastric stage		Intestinal stage		Residual stage		
		Mean ± SD (n = 3)	%	Mean ± SD (n = 3)	%	Mean ± SD (n = 3)	%	
Cr	130.2 ± 4.8	8.05 ± 0.43	7.6	9.62 ± 0.57	9.1	88.3 ± 8.5	83.3	106
Mn	4980 ± 207	1591.7 ± 34.5	30.8	606.6 ± 14.2	11.8	2963 ± 101	57.4	5161
Ni	69.1 ± 3.3	6.64 ± 0.30	11.7	3.64 ± 0.14	6.4	46.5 ± 2.2	81.9	56.8
Cu	25.0 ± 2.8	1.38 ± 0.10	5.8	2.60 ± 0.14	10.8	20.0 ± 1.3	83.4	24.0
Zn	133.4 ± 3.8	18.83 ± 0.83	13.0	1.90 ± 0.27	1.3	124.6 ± 2.3	85.7	145.3
Mo	4.2 ± 0.4	0.60 ± 0.03	13.2	0.62 ± 0.01	13.6	3.32 ± 0.18	73.2	4.5
Cd	0.91 ± 0.02	0.24 ± 0.01	32.9	0.04 ± 0.00	5.5	0.45 ± 0.01	61.6	0.73
Pb	59.8 ± 0.4	0.33 ± 0.03	0.6	0.88 ± 0.06	1.5	58.8 ± 6.1	98.0	60.0

Table 2.4 (continued)
(c) Data from week 3

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3.3.4. Approach 2:
"Stomach + Intestine"
Extraction

2. With the screw cap closed, manually shake the soil–fluid mixture.
 3. After 5–15 min, add 13.5 mL of simulated gastric fluid.
 4. The mixture is then shaken on an end-over-end shaker maintained at $37 \pm 2^\circ\text{C}$.
 5. After 1 h check the pH of the soil suspensions; the pH should be 1.2–1.7 (*see Note 13*).
 6. The solution is centrifuged at 3000 rpm for 5 min and a 1.0 mL aliquot of supernatant is removed.
 7. To the supernatant add 9.0 mL of 0.1 M HNO_3 .
 8. The sample is then stored at $<8^\circ\text{C}$ prior to analysis by ICP-MS (*see Notes 10 and 11*).
1. 0.6 g (accurately weighed) of sample is placed into a 50 mL screw-cap Sarstedt tube and treated with 9 mL of simulated saliva fluid (*see Note 12*).
 2. With the screw cap closed, manually shake the soil–fluid mixture.
 3. After 5–15 min, add 13.5 mL of simulated gastric fluid (*see Note 12*).
 4. The mixture is then shaken on an end-over-end shaker maintained at $37 \pm 2^\circ\text{C}$.
 5. After 1 h check the pH of the soil suspensions; the pH should be 1.2–1.7 (*see Note 13*).
 6. Then, add 27.0 mL of simulated duodenal fluid and 9.0 mL of simulated bile fluid (*see Note 12*).
 7. With the screw cap closed, manually shake the soil–fluid mixture.
 8. Adjust the pH of the resultant suspension to 6.3 ± 0.5 by the drop-wise addition of 37% HCl, 1 M or 10 M NaOH, as required.
 9. The mixture is then shaken on an end-over-end shaker maintained at $37 \pm 2^\circ\text{C}$ for 4 h.
 10. Remove the soil suspension.
 11. Measure (and record) the pH of the soil suspension; pH should be 6.3 ± 0.5 .
 12. The soil suspension is then centrifuged at 3000 rpm for 5 min and a 1.0 mL aliquot of supernatant is removed.
 13. To the supernatant is added 9.0 mL of 0.1 M HNO_3 .
 14. The sample is then stored at $<8^\circ\text{C}$ prior to analysis by ICP-MS (*see Notes 10 and 11*).

865 **3.4. Method: Soil**
866 **Digestion Procedure**
867

868 **3.4.1. Acid Digestion**
869 **Procedure**
870

An acid digestion procedure is used to provide pseudo-total metal analysis.

- 871 1. Approximately 1 g of soil sample is accurately weighed into
872 a digestion tube (250 mL volume).
- 873 2. Add 0.5–1.0 mL of water to obtain a slurry.
- 874 3. Then add, while mixing, 7 mL of 12.0 M HCl, followed
875 by 2.3 mL of 15.8 M HNO₃ (drop by drop, if necessary to
876 reduce foaming) (*see Note 8*).
- 877 4. Add 15 mL of 0.5 M HNO₃ to the reaction vessel and
878 connect to a water-cooled reflux condenser.
- 879 5. Allow to stand for 16 h at room temperature to allow slow
880 oxidation of the organic matter of the soil.
- 881 6. Raise the temperature of the reaction mixture until reflux
882 conditions are achieved and maintain for 2 h.
- 883 7. Allow to cool slowly to room temperature.
- 884 8. Rinse the contents of the condenser into the reaction vessel
885 with 10 mL of 0.5 M HNO₃.
- 886 9. Quantitatively transfer the contents of the reaction vessel
887 to a 100 mL volumetric flask. Rinse the vessel with 0.5 M
888 HNO₃ and transfer as well. Make up to the mark with
889 water, stopper and shake.
- 890 10. Allow the undissolved matter to settle and then analyse the
891 supernatant solution by ICP-MS (*see Notes 10 and 11*).

892
893 **3.4.2. Alternate Acid**
894 **Digestion Procedure**
895

- 896 1. Approximately 1 g of soil sample is accurately weighed
897 into a digestion tube and 10 mL of 1:1 v/v concentrated
898 HNO₃:water is added.
- 899 2. The mixture is then heated at 95°C on a heating block for
900 15 min without boiling.
- 901 3. After cooling at room temperature for 5 min, 5 mL con-
902 centrated HNO₃ is added and the sample is heated at 95°C
903 for 30 min.
- 904 4. An additional 5 mL of concentrated HNO₃ is added until
905 no brown fumes are given off.
- 906 5. Evaporate the solution to <5 mL.
- 907 6. After cooling, 2 mL of water and 3 mL of 30% H₂O₂ are
908 added and heated (<120°C) until effervescence subsides
909 and the solution cools. Additional H₂O₂ is added until
910 effervescence ceased (but add no more than 10 mL H₂O₂).
911 This stage is continued for 2 h.
- 912 7. Evaporate the solution to <5 mL.

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8. After cooling, add 10 mL of concentrated HCl and heat (<120°C) for 15 min.
9. After cooling, filter the sample through a Whatman No. 41 filter paper into a 100 mL volumetric flask, and then make up to the mark with water.
10. Analyse by ICP-MS (*see* **Notes 10 and 11**).

3.5. Method: Sample Analysis by ICP-MS

ICP-MS measurement conditions are optimised daily using the built-in PlasmaLab software procedure. Samples of the soil extracts/digests are analysed by ICP-MS using an external calibration technique. Sc, In and Tb internal standards (10 µg/L) are added to all samples, blanks and standard solutions. A blank is analysed with each analytical batch (*see* **Note 9**).

3.5.1. ICP-MS Operating Conditions: Standard Mode

1. In standard mode the following elements can be analysed: >90 amu
2. Forward power, 1400 W; coolant gas flow, 13.0 L/min; auxiliary gas flow, 0.90 L/min; nebuliser gas flow, 0.80 L/min; quadrupole bias, -1.0 V; hexapole bias, 0.0 V; dwell time per isotope, 10 ms.

3.5.2. ICP-MS Operating Conditions: Collision/Reaction Cell Mode

1. In collision/reaction cell mode the following elements can be analysed: <90 amu
2. Forward power, 1400 W; coolant gas flow, 13.0 L/min; auxiliary gas flow, 0.90 L/min; nebulizer gas flow, 0.80 L/min; collision cell gas, 4.50 L/min of 7% H₂/93% He; quadrupole bias, -14.0 V; hexapole bias, -15.0 V; dwell time per isotope, 10 ms.

4. Notes

1. Unless otherwise stated, all solutions should be prepared in water that has a resistivity of 18.2 M^Ω × cm. This standard is referred to in the text as “water”.
2. All laboratory ware should be made of borosilicate glass, polypropylene, polyethylene or PTFE, except for the centrifuge tubes, which should be made of borosilicate glass or PTFE.
3. All vessels in contact with samples or reagents should be cleaned in HNO₃ (4 mol/L) for at least 30 min, then rinsed with distilled water, cleaned with 0.05 mol/L EDTA and rinsed again with distilled water. Alternatively clean all

Heavy Metal Bioavailability

vessels by immersing in HNO_3 (4 mol/L) overnight and then rinse two to three times with water.

4. When extracting with sodium nitrate (NaNO_3), it is necessary to correct the results for the difference in final volume, i.e. 2 mL of HNO_3 was added to 48 mL of extract to give a final volume of 50 mL.
5. When using sequential extraction methods for the analysis of sediment or soil samples, a separate sub-sample should be dried (in a layer of approximately 1 mm depth) in an oven at $105 \pm 2^\circ\text{C}$ for 2–3 h, transferred to a desiccator and allowed to cool prior to weighing.
6. Ensure that the sample, i.e. sediment/soil, does not form a “cake” during the extraction procedure. If a cake is formed, either adjust the shaking speed to ensure that the suspension is maintained or mechanically break the solid “cake” with a pre-cleaned glass rod. It is important that the sample remain in complete suspension during the extraction process.
7. In sequential extraction the mechanical shaker, preferably of the end-over-end type, should be operated at a speed of 30 ± 10 rpm and a temperature of $22 \pm 5^\circ\text{C}$. All samples should be centrifuged at $3000g$ for 20 min.
8. The combination of 12.0 mol/L HCl and 15.8 mol/L HNO_3 in a volume ratio of 3:1, respectively, is known as aqua regia.
9. Calibration solutions for ICP-MS should be prepared with the appropriate extraction solution, i.e. use matrix-matched calibration solutions.
10. It is important to prepare a sample blank for every batch of extractions, i.e. prepare a container with no sediment/soil, but treated in the same manner as though it contained the sample.
11. It is recommended for ICP-MS that all extracts be filtered ($0.45 \mu\text{m}$) prior to analysis.
12. Simulated gastrointestinal fluids are stored at room temperature overnight prior to use. Prior to their use for bioaccessibility studies, the fluids need to be heated to 37°C at least 2 h before their use on the day following their preparation.
13. If the pH of a sample suspension is not within the guideline of 1.2–1.7, the sample should be discarded and sub-samples re-extracted. Before re-extracting, however, add an additional amount of 37% HCl (up to a maximum of 1.0 mL).

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Acknowledgements

The author would like to thank Dr Marisa Intawongse for evaluation of some of the methods described. Also, the technical assistance of Mr. Gary Askwith is acknowledged.

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