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3 1 **Residues characterisation from the fluidised bed combustion of East London's**
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5 2 **solid recovered fuel**
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18 **Abstract**

19 Waste thermal treatment in Europe is moving towards the utilisation of the
20 combustible output of mechanical, biological treatment (MBT) plants. The
21 standardisation of solid recovered fuels (SRF) is expected to support this trend and
22 increase the amount of the generated combustion residues. In this work, the residues
23 and especially the fly ashes from the fluidised bed combustion (FBC) of East
24 London's NCV 3, Cl 2, and Hg 1 class SRF, are characterised. The following toxicity
25 indicators have been studied: leachable chlorine, organochlorides expressed as
26 pentachlorobenzene and hexachlorobenzene, and the heavy metals Cu, Cr, Cd, Zn, Ni,
27 and Pb. Furthermore the mineralogical pattern of the ashes has been studied by means
28 of XRD and SEM- EDS. The results suggest that these SRF derived ashes have
29 significantly lower quantities of Cu, Cd, Pb, Zn, leachable Cl and organochlorides
30 when compared to other literature values from traditional waste thermal treatment
31 applications. This fact highlights the importance of modern separation technologies
32 employed in MBT plants for the removal of components rich in metals and chlorine
33 from the combustible output fraction of SRF resulting to less hazardous residues.

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42 **Keywords:** Refuse derived fuels, thermal treatment, air pollution control residues,
43 trace metals, chlorine leaching

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3 44 **1. Introduction**
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6 45 Thermal treatment has been recognized as a valuable technique for the recovery of the
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8 46 energy content of wastes within the waste management hierarchy. Recent data (Defra,
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10 47 2009) indicate that countries like Denmark, Netherlands, Belgium, Sweden,
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12 48 Luxemburg, Germany, France and Portugal, incinerate more than 20% of their
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14 49 generated municipal solid waste. In addition, or in replacement, of traditional mass
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16 50 grate thermal treatment, the use of the combustible output fractions of MBT plants
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18 51 could further support a sustainable short/middle- term approach for the management
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20 52 of the increasing volumes of wastes, especially in dense metropolitan areas (Caputo
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22 53 and Pelagagge, 2002). This integrated waste treatment approach has increased its
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24 54 presence in Europe, with MBT plants that reach a capacity of 2 million tons per
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26 55 annum (Velis et al., 2009).
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28 56 Despite these facts, public opinion is sometimes against developments regarding
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30 57 integrated thermal treatment applications, even in developed counties (Luria, 2008).
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33 58 These oppositions mainly focus on direct health effects from emissions and residues
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35 59 of these technologies based on past experience. Issues related to chlorine and heavy
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37 60 metals content of waste derived fuels have resulted to limited demand of the latter
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39 61 during the past decade (Rotter et al., 2004).
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42 62 In this context, the standardization of SRF (CEN/TS 15359, 2006) in terms of
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44 63 calorific value, trace metals and chlorine content, intends to facilitate the economic,
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46 64 emissions, and technological issues associated with the acceptance and marketability
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48 65 of waste derived fuels and related applications. According to the abovementioned
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50 66 standard, SRF is distinguished from the classical term of refuse derived fuel (RDF), as
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67 the initial characterization criterion is a non-hazardous waste source and the final
68 criterion is a quality assured (QA) classification according to the following properties:

- 69 • The mean net calorific value
- 70 • The mean value of chlorine content
- 71 • The mean and 80th percentile values for mercury content. Both values are
72 taken into account and due to the statistical distribution pattern of Hg. The
73 highest value is used for determination of the SRF class.

74 Each property is divided in five classes with range values and the combination of the
75 property classes makes up the class code for each SRF.

76 SRF standardization protocols can support the development and expansion of waste-
77 fuel markets (Bernd et al., 2007). This expansion is expected to increase the quantities
78 of the generated combustion and air pollution control (APC) residues. In the UK this
79 amount is expected to reach 162,000 tons per annum in 2010, from about 83,000 tons
80 in 2000 (Amutha Rani et al., 2008). Fly ash in particular, is an issue of concern as it is
81 enriched with heavy metals, soluble salts and organic micro-pollutants (Huang et al.,
82 2003; He et al., 2004; Hyks et al., 2009), that could be released in the environment
83 from its utilization or landfilling. Thus, knowledge of the characteristics of these
84 residues is of extreme importance for their treatment within good integrated waste
85 management practices.

86 This work characterizes the fly ashes produced from the combustion of East London's
87 SRF in a fluidized bed reactor. The following toxicity indicators have been studied:
88 total organic carbon (TOC), leachable chlorides, organochlorides expressed as
89 pentachlorobenzene (Cl₅Bz) and hexachlorobenzene (Cl₆Bz), and the heavy metals
90 Cu, Cr, Cd, Zn, Ni, and Pb. Finally, XRD and SEM- EDS techniques are utilized for
91 the mineralogical characterization of the produced fly ashes. These commonly applied

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92 indicators have been employed to facilitate comparisons with other reported values in
93 literature. The aim of this study is to assess whether the pollutants load of SRF
94 derived fly ashes is lower than the equivalent values reported in literature, from
95 conventional waste fuels, and/ or traditional waste thermal treatment applications.

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97 **2. Materials and methods**

98 **2.1. Feedstock properties**

99 SRF derived from East London's Waste Authority, processed by a private contractor
100 was the feedstock for the trial. The fuel is produced in a sequential separation,
101 shredding, and aerobically bio-drying MBT process, classified as a "NCV 3; Cl 2; Hg
102 1" class SRF. A batch of 100kg was sampled from the MBT plant and it was later
103 sub-sampled as a static pile, according to the relevant standard (CEN/TS 15442, 2006)
104 for the detailed investigation of proximate characteristics and chlorine content. The
105 remaining data on ultimate analysis (Table 1) were provided by the SRF producer
106 based on routine quality analysis/ quality control (QA/QC).

107 <<Table 1>>

108 **2.2. Fluidized bed combustion rig operating conditions**

109 The 50 kW_{th} fluidized bed combustor that was used for the trial consisted of a screw
110 feeding hopper, the main bed chamber (dimensions 175× 30× 30 cm), a secondary
111 combustion chamber that leads to a vertical ash deposition compartment, a water heat
112 exchanger, a cyclone, and an exhaust fan prior to the stack. The bed area was filled
113 with 30.2 kg of silica sand with particle size between 1.00 – 0.5 mm (16/30 grade,
114 density 1,556 g l⁻¹), resulting to bed static dimensions of 30*30*15.35 cm. The FBC
115 was vacuumed the day before the experiment for the removal of residual ash and

116 particles from previous trials. Furthermore, it was operated overnight, burning natural
117 gas for decontamination and start-up purposes. The rig was monitored by 19 K-type
118 thermocouples, CO, CO₂, and O₂ online gas monitoring systems. The SRF incoming
119 flow slightly varied throughout the trial with a mean value of 117g min⁻¹ and a lambda
120 coefficient equal to 1.6. The duration of the test was 300 minutes and the bed
121 temperature was at 800 ± 20 °C. The rig and the ashes sampling points are illustrated
122 in Figure 1. Detailed information on the experimental conditions are reported in
123 previous work (Balampanis et al., 2008).

124 <<Figure 1>>

125 **2.3. Analysis**

126 **2.3.1. Inorganic chlorine & chlorobenzenes**

127 After the experiment, the rig was disassembled and the mixed silica sand/ bed ash
128 were collected, weighted, and emptied to a tank with deionised water. The tank was
129 mechanically agitated for 3 hours and 6 replicate samples were taken, centrifuged and
130 filtrated. The horizontal chamber and cyclone ash were collected separately in clean
131 pre- weighted vacuum bags. Ashes sampled from the horizontal chamber
132 (approximate size <1.2 mm) and ashes sampled from the cyclone (approximate size <
133 200 µm) (Figure 2) will be referred herein and after, as coarse fly ash and fine fly ash,
134 respectively, according to the literature definitions (IAWG, 1997; Quina et al.,
135 2008a). Six replicates of a gram each, of coarse and fine fly ash were diluted in 250
136 mL of deionised water and agitated for three hours. The mix was centrifuged and
137 decanted and the filtrate was stored in polypropylene bottles, at 4 °C for chloride
138 anions analysis (Dionex, UK- Ion Chromatographer, column: Ion Pac As9- HC 4*250
139 mm).

140 For the determination of Cl₅Bz and Cl₆Bz the following procedure was employed.
141 Seven replicates of each ash type were spiked with extraction standards (800ng mL⁻¹
142 1,3,5-tribromobenzene in toluene) and then digested with 100mL of 2M HCl. The mix
143 was separated using vacuum filtration, and the cakes were washed with deionised
144 water to reduce acidity, air-dried for 12h, and then extracted with Soxhlet using
145 200mL of toluene for 20h. The aqueous solutions were extracted three times with
146 100mL of dichloromethane per litre of solution, and the solvent extracts were washed
147 twice with deionised water for pH adjustment (50% v/v). The two extracts from each
148 sample were mixed, concentrated using a rotary evaporator (38 °C, 68 mbar), filtered
149 through a multilayer silica gel column (anhydrous Na₂SO₄ , 10% AgNO₃ silica gel,
150 20% H₂SO₄ silica gel, 40% H₂SO₄ silica gel, 30% KOH silica gel) and eluted with
151 hexane, double the height of the column. The column's elutes were further
152 evaporated (35 °C, 200 mbar) and finally concentrated to 1mL using a nitrogen flow
153 concentrator. The samples were spiked again with recovery standards (100 µl of
154 1.6µg mL⁻¹ of 1,2 dichlorobenzene-d₄) and analysed through GC-MS-SIM
155 (Instrument: Perkin Elmer- Autosystem XL/Turbo Mass Gold; Column: Thames-
156 Restek Rtx ®- 1MS- 100% dimethyl polysiloxane column (length 15m, internal
157 diameter 0.25 mm, film thickness 0.25 µm); Injection: 1 µl at a split ratio of 100:1;
158 Ionisation mode: positive 70 eV; Oven temperature conditions: initial 50 °C, rising 30
159 °C min⁻¹ up to 125 °C, and then 15 °C min⁻¹ up to 300 °C where it was held for 6 min).

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161 **3.3.2. Heavy metals**

162 Standard methods (ASTM, 2004) for the determination of heavy metals in combustion
163 residues, involve the utilisation of hydrofluoric acid (HF). These methods were
164 excluded from this work due to HF's adverse effects on instrumentation, and for

165 health and safety reasons. Furthermore, the total content of heavy metals is not
166 directly related to the leaching potential of fly ash, when landfilled (Hyks et al.,
167 2009). Thus, four HF free digestion methods were tested for their recoveries, using a
168 certified reference material (CRM). The CRM was MSW incineration fly ash (BCR-
169 176R, Joint Research Centre, Institute for Reference Materials and Measurements,
170 EC) and a summary of the digestion methods is presented in Table 2.

171 <<Table 2>>

172 An Anton Parr Multiwave 3000 microwave oven unit was utilised for the microwave
173 assisted digestion (MWAD) methods (A, B, and C), and compared against standard
174 reflux with aqua regia (method D) (BSI, 1995). For method A, seven replicates of 400
175 ± 1 mg CRM and a method blank were placed in the PTFE pressure vessels with 8 mL
176 of concentrated (15.8 M) nitric acid. The vessels were left 16 hours in a fume
177 cupboard to equilibrate, to avoid elevated pressures inside the vessels at the MWAD
178 stage. The following MWAD programme was applied: 20 minutes for the instrument
179 to reach 18 bar and 190 °C, where held for 20 minutes and finally another 20 minutes
180 for the vessels to cool down. The mixture was then filtered using 0.45 μ m Whatman
181 cellulose filter papers and diluted with ultra pure (MilliPore) water, to a fixed volume
182 of 100 mL.

183 Method B was performed exactly as method A, but with a different acid mix: 5 mL of
184 nitric acid and 3mL of hydrogen peroxide (100 volumes). Method C was performed
185 exactly as method A, with the difference that ultrasonic waves were applied through a
186 600W probe (Langford Ultrasonics- Sonomatic), to test whether ultrasonication could
187 enhance the digestion reactions.

188 Method D was tested on 7 CRM replicates of 3 ± 0.001 g each, and a method blank.

189 Twenty one mL of concentrated hydrochloric acid (12 M) were added in 250mL

190 reaction flasks, followed by 7 mL of nitric acid. The mix was allowed to oxidise at

191 room temperature for 16h, and then heated to reflux conditions for 2h. After cooling

192 down, it was filtered (0.45 μ m Whatman cellulose filter papers) and made up to 100

193 mL using ultra pure water. All chemicals were trace analysis grade and purchased

194 from Fischer Scientific UK. The quantification was achieved through a graphite

195 furnace/ flame- atomic absorption spectrometer (GF/F-AAS) A-Analyst 800 Perkin

196 Elmer instrument, equipped with an air/ acetylene flame and an AS-90 autosampler.

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198 **3.3.3. XRD, TOC & SEM- EDS analysis**

199 The coarse and fine fly ashes were also analysed for their total C,H,N, and TOC

200 content using an elemental analyser (Vario EL III), and further examined in a SEM-

201 EDS microscope (Philips XL 30) for their major elements determination. The mean

202 concentration of elements (% wt> 1) in the SEM- EDS analysis was obtained from a

203 spectrum over a 4 mm² and 0.16 mm² area for coarse and fine fly ash, respectively;

204 Furthermore, the reported deviations represents 4 different scans in smaller areas, on

205 each one of the quadrants of the originally scanned areas. Finally, XRD (Siemens ED

206 5005) analysis was employed for the determination of the ashes' crystalline phases.

207 **4. Results and discussion**

208 **4.1. Inorganic chlorine and chlorobenzenes**

209 Figure 3 demonstrates the amount of water soluble chlorides that leached from each
210 ash type. As expected the bed ash contained the lowest levels of Cl as most of it was
211 volatilised in the process to form HCl, Cl₂, or Cl radicals. The bed ash contained an
212 amount of non- combustibles that was visible in the bed material. These residues were
213 mostly glass fractions, ceramics, metals, stones etc., thus a rather abnormal and
214 heterogeneous distribution of chlorides in these particles should be expected.
215 Although the determination of chloride ions was made with a much greater liquid to
216 solid (L/S) ratio than characterisation protocols suggest (BSI, 2002), the bed ash,
217 based on the leached Cl⁻, would be accepted for co-disposal in a non hazardous
218 landfill (Cl⁻ < 15,000 mg kg⁻¹), according to the existing legislation (EC, 2002) for
219 granular waste. According to the same legislation the coarse fly ash would be
220 accepted in a hazardous waste landfill without further treatment (Cl⁻ < 25000 mg kg⁻¹),
221 while fine fly ash would require further stabilisation before final disposal.

222 The higher chlorinated benzenes (Cl₅Bz, and Cl₆Bz) were quantified as indicators for
223 the organochloride load of the fly ashes. Indirect measurement of dioxins like
224 compounds using Cl₅Bz, and Cl₆Bz is useful for process optimisation, control of
225 separation efficiencies of the flues gases in cleaning devices and the control of
226 emissions levels. However, although indirect measurements can be performed at
227 lower cost than determination of PCDD/Fs, the relationship between PCDD/Fs and
228 the indicator parameters is likely to be plant specific (Öberg et al., 2008). The Cl₅Bz
229 values ranged between 9± 3.9 ng g⁻¹ for coarse, and 15± 2.8 ng g⁻¹ for fine fly ash
230 while the equivalent Cl₆Bz values ranged between 3.3± 2.8 ng g⁻¹, and 8± 2 ng g⁻¹,

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231 respectively. These figures correspond to the lower range of reported values on
232 organochlorides within the literature as it will be discussed at a later stage (section
233 4.4).

234 <<Figure 2>>

235 **4.2. Heavy Metals**

236 The four HF-free fly ash digestion methods were compared for their recoveries of the
237 CRM and the results are reported in Figure 4. The overall recoveries ranged between
238 59% and 94%, except from Cr which ranged at lower levels ca. 19- 38%. A one way
239 ANOVA at a confidence interval of 95%, confirmed that there was no single method
240 that significantly recovered higher amounts for the whole range of the examined
241 metals. However, some exceptions were found in method A, which recovered
242 significantly higher quantities of Pb, and in the aqua regia method (D), which
243 recovered lower amounts of Cu, Cd and Pb. Furthermore, neither the addition of H₂O₂
244 in the digestion vessels, or ultrasonication as post-digestion treatment, improved the
245 recovery of the metals. Thus, single step HNO₃ MWAD proved sufficient for the
246 solubilisation of heavy metals in waste derived fly ashes, as reported in older studies
247 (Mester et al., 1999; Quina et al., 2008b).

248 <<Figure 3>>

249 The fly ashes were further analysed for their content in Cu, Cr, Ni, Pb, Cd, and Zn
250 using method A and the results are presented in Figure 5. Coarse fly ash contained
251 higher Cu, Pb and Zn quantities than the fine fly ash fraction, which had higher Cr
252 and Ni contents. The Cd values were relatively low ranging at $3.6 \pm 0.6 \text{ mg kg}^{-1}$ and
253 $7.3 \pm 0.2 \text{ mg kg}^{-1}$ for fine and coarse fly ash, respectively. Finally, it should be noted
254 that the actual concentration of Cr in both ash types could be higher than the ones

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255 presented in Figure 5, as the HF free digestion method used gives a relative poor
256 recovery of the element according to the CRM recovery values.

257 <<Figure 4>>

258 **4.3. Minerals and carbon**

259 The rough (%wt >1) composition of the elements in the ashes, as recognised in SEM-
260 EDS analysis is presented in Table 3. Calcium, silicon, aluminium, chlorine, sodium,
261 potassium, iron, sulphur, and phosphorus were the most common elements, besides
262 carbon, which ranged at 8.6 ± 0.1 % and 9.6 ± 0.2 % for the coarse and fine fly ash,
263 respectively. This slight difference in the total carbon content is probably due to the
264 greater residence time of the bigger and heavier coarse particles (Figure 2 a and b) in
265 the combustion zone, resulting to higher C to CO₂ conversion. This finding is
266 confirmed by the TOC levels that ranged at 6 ± 0.4 % and 6.8 ± 0.1 % for coarse and
267 fine fly ash particles. In respect to the SEM-EDS sensitivity, another conclusion is
268 that fine fly ash had about double the amount of chlorine than the coarse one. This
269 finding is confirmed by the amount of water soluble chlorides that leached from each
270 ash type (section 4.1).

271 The mineralogical analysis recognised the main crystal phases of the ashes by means
272 of XRD and the diffractograms are presented in Figure 6. These were similar for both
273 ash types: Calcite (CaCO₃), quartz (SiO₂), halite (NaCl), sylvite (KCl), and calcium
274 sulphate (CaSO₄); except from calcium silicate (CaSiO₄), which was only detected in
275 fine ash particles. The XRD pattern is similar to most MSWI fly ashes as reported in
276 other works (Wan et al., 2006; Quina et al., 2008b; Wang et al., 2008; Shi and Kan,
277 2009) with the exception of calcium silicate. This finding is of particular importance
278 as layers of CaSiO₄ can interfere as heat transfer barriers in flame retardant

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279 applications (Hamdani et al., 2009), however its presence was not confirmed at the
280 heat- exchange tower (coarse fly ash sampling point), but only at the cyclone (fine fly
281 ash collection point.

282 <<Table 3>>

283 <<Figure 5>>

284 <<Figure 6>>

285 **4.4. Comparison of SRF fly ash with literature values**

286 Comparisons against literature values are often limited by the heterogeneity of
287 available data, due to the complexity of the ash products, and the high number of
288 available methods for residues characterisation, leaching protocols etc. Table 4
289 presents the toxicity indicators determined in this work, against equivalent values
290 from MSWI derived fly ashes in literature. The selection of the literature data was
291 based on the quality of the reported results, and the methods used to obtain them.

292 The results indicate lower levels of some pollutants in SRF- derived fly ashes
293 compared to the reported values in literature. The chlorobenzenes in the examined
294 samples range at an order of magnitude lower than other reported figures. The same
295 result is obtained when comparing the heavy metals content of the SFR fly ashes with
296 the equivalent metals load from other works; The levels of, Cd, Cu, Pb and Zn were
297 significantly lower than other reported values. Furthermore, the leached chlorides
298 levels lay on the lowest reported ranges within literature. However, no particular
299 difference was observed for Cr and Ni and TOC, which ranged at the same levels as
300 other researchers report.

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301 The reported values in literature might involve data from thermal treatment
302 technologies different than FBC, e.g. mass grate incineration, and can enhance the
303 heterogeneity of data. As reported in other works (Lind et al., 2007) when comparing
304 grate firing and FBC, there were differences in the levels of As and Sb in the
305 generated fly ashes. However, the low Cl, Cd, Cu, Pb, Zn, Cl₅Bz, and Cl₆Bz presented
306 in Table 4 clearly reflect the low chlorine and metals content of the particular fuel.
307 This fact indicates the importance of modern separation technologies that are used in
308 MBT plants for the removal of components rich in metals and chlorine like electronic
309 waste and hard plastics, respectively, resulting to the removal of heavily polluted
310 components from the combustible output fractions (Rotter et al., 2004).

311 <<Table 4>>

312 **5. CONCLUSIONS**

313 The coarse and fine fly ashes produced from the fluidised bed combustion of a NCV
314 3, Cl 2, and Hg 1 class SRF have been characterised using commonly tested toxicity
315 indicators like TOC, Cd, Pb, Zn, Ni, Cr, Cu, Cl_{5,6}Bz, and water soluble Cl. Our
316 findings indicate that SRF derived fly ashes have a similar mineralogical pattern with
317 other waste- derived fly ashes, with the exception of calcium silicate, which was only
318 detected in the fine particles.

319 The results, when compared with other literature values indicate that, these SRF
320 derived fly ashes have significantly lower values in Cu, Cd, Pb, Zn, leachable Cl and
321 organochloride load than other traditional thermal treatment applications. This fact
322 highlights the importance of modern separation technologies employed in MBT plants
323 for the removal of components rich in metals and chlorine from the combustible
324 output fraction of SRF.

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414 Table 1

415 SRF properties

Proximate analysis mean± s (% wt **)	
Moisture content	13.2 ± 1.5
Ash content	13.7 ± 2

Ultimate analysis mean ± s(% wt dm)	
C	47.4 ± 4.2
H	5.7 ± 2.9
N	0.8 ± 0.3
S	0.1 ± 0.02
Cl	0.4 ± 0.02
O*	45.1

* By difference

** Weight percentage- as received

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420 Table 2

421 Summary of digestion methods

Method	Reagents	Digestion conditions
A	8 mL HNO ₃	MWAD 190°C, 18 bar
B	3 mL H ₂ O ₂ + 5 mL HNO ₃	MWAD 190°C, 18 bar
C	8 mL HNO ₃	MWAD 190°C, 18 bar + ultrasonication
D	21mL HCl+ 7 mL HNO ₃	Equilibration 16 hr, reflux 2 hr

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424 Table 3

425 SEM-EDS results on elemental composition %wt> 1(x: mean, s: standard deviation)

Composition (wt%)	Coarse fly ash		Fine fly ash	
	x	s	x	s
Na	1.3	0.7	1.7	0.3
Al	1.7	0.5	2.5	0.3
Si	5	2.7	5.5	2.8
P	1.3	0.8	1	0.2
S	1.2	0.6	1.4	0.2
Cl	2.2	0.7	5.5	0.7
K	1.4	0.5	2.3	0.4
Ca	11	1.2	9	0.7
Fe	1.3	0.5	1.6	0.3

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428 Table 4
 429 Comparison of East London's SRF fly ash indicative toxicity indicators with literature
 430 values

	This study	MSWI fly ash UK ^a	MSWI fly ash Sweden ^b	MSWI fly ash other ^c	MSWI fly ash other ^d
Cl* mg g ⁻¹	15-45	140-170	6-81	45-380	nd
TOC mg g ⁻¹	56- 69	10- 250	Nd	4.9- 17	1.6- 400
Cd mg g ⁻¹	0.003- 0.007	0.1- 0.15	0.0035- 0.31	0.016- 1.6	0.2
Pb mg g ⁻¹	0.76- 1.22	2.5- 3.5	0.73- 36	0.25- 27	0.88
Zn mg g ⁻¹	0.8- 1.23	4- 8.5	4.9- 44	4.3- 104	21.3
Cu mg g ⁻¹	0.36- 0.47	0.35- 0.6	0.22- 1.8	0.016- 2.22	1.74
Cr mg g ⁻¹	0.41- 1.07	0.012- 0.2	0.2- 1.6	0.072-0.57	0.121
Ni mg g ⁻¹	0.18- 0.42	0.015- 0.035	0.036-0.11	0.02-0.71	nd
Cl ₅ Bz ng g ⁻¹	5.1- 17.8	nd	43- 610	nd	189- 355
Cl ₆ Bz ng g ⁻¹	0.5- 10	nd	47- 260	nd	113- 249

431 nd- not determined

432 * Water soluble or total

433 ^a Aqua regia total metals (Amutha Rani et al., 2008)

434 ^b Total content (Öberg et al., 2007)

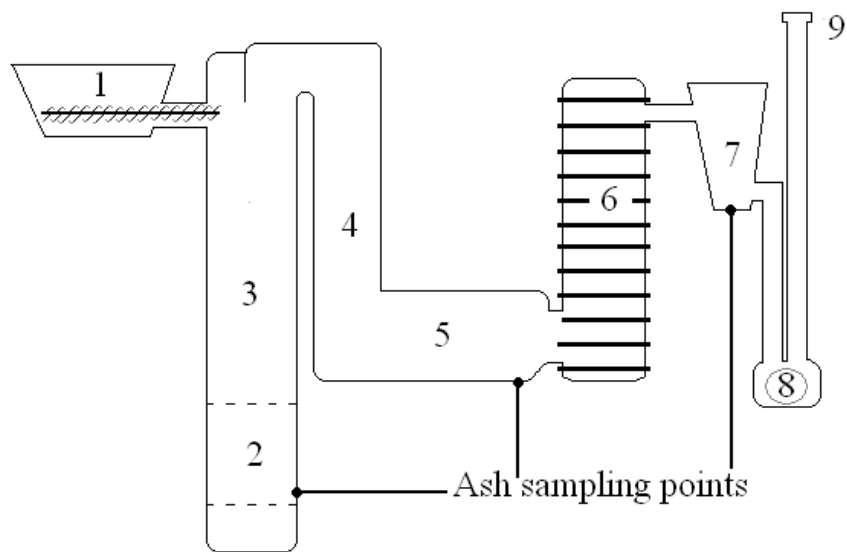
435 ^c Total (Quina et al., 2008a)

436 ^d Total (Huang et al., 2003)

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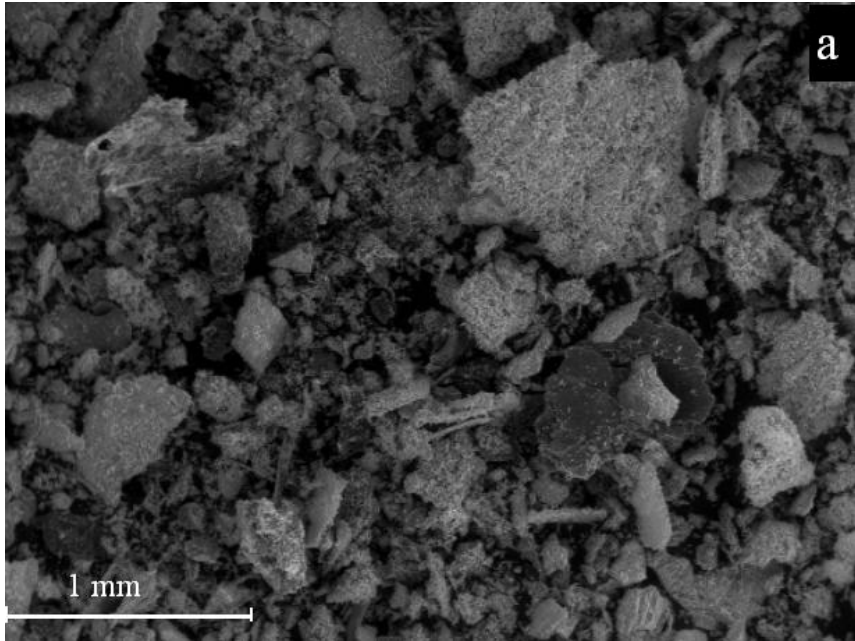
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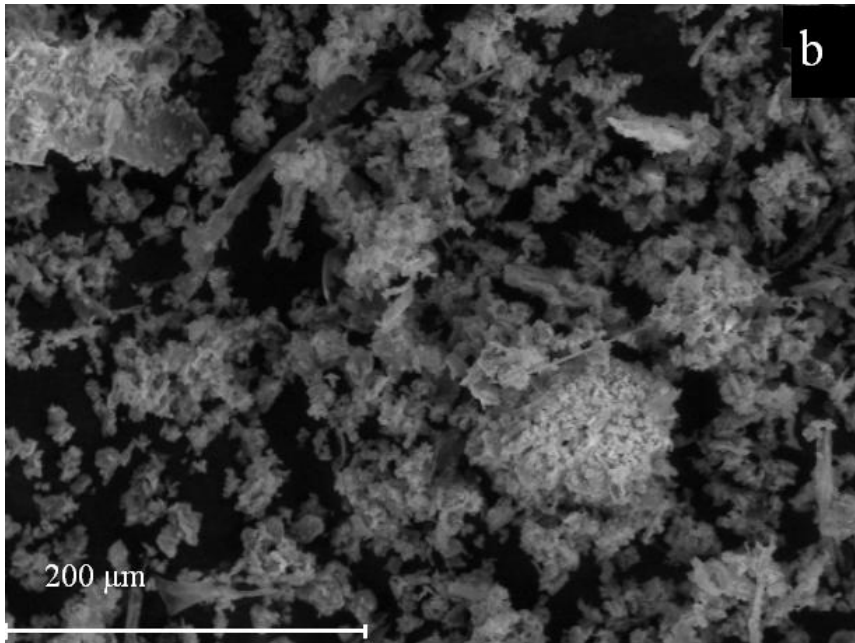
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439 Figure 1. Fluidized Bed Combustor- 1: screw feeding hopper, 2: bed area, 3: FB
440 chamber, 4: vertical secondary combustion chamber, 5: horizontal chamber- ash
441 deposits area, 6: heat exchange tower, 7: cyclone, 8: exhaust fan, 9: stack
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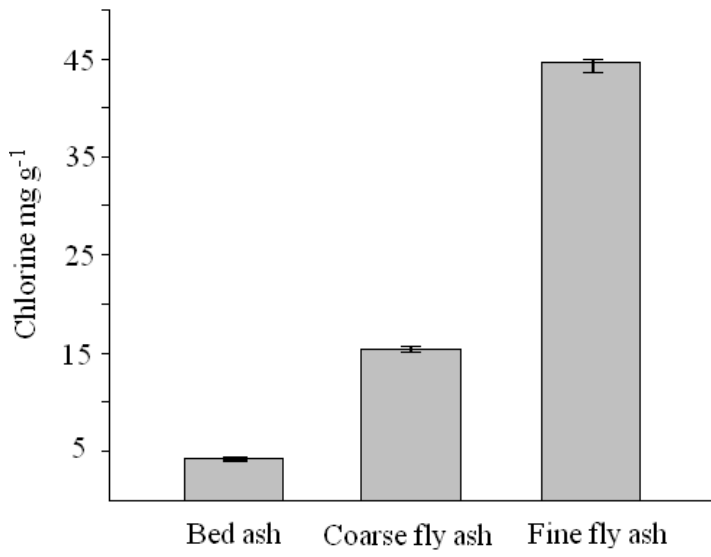
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446 Figure 2. SEM pictures. (a) coarse, (b) fine fly ash

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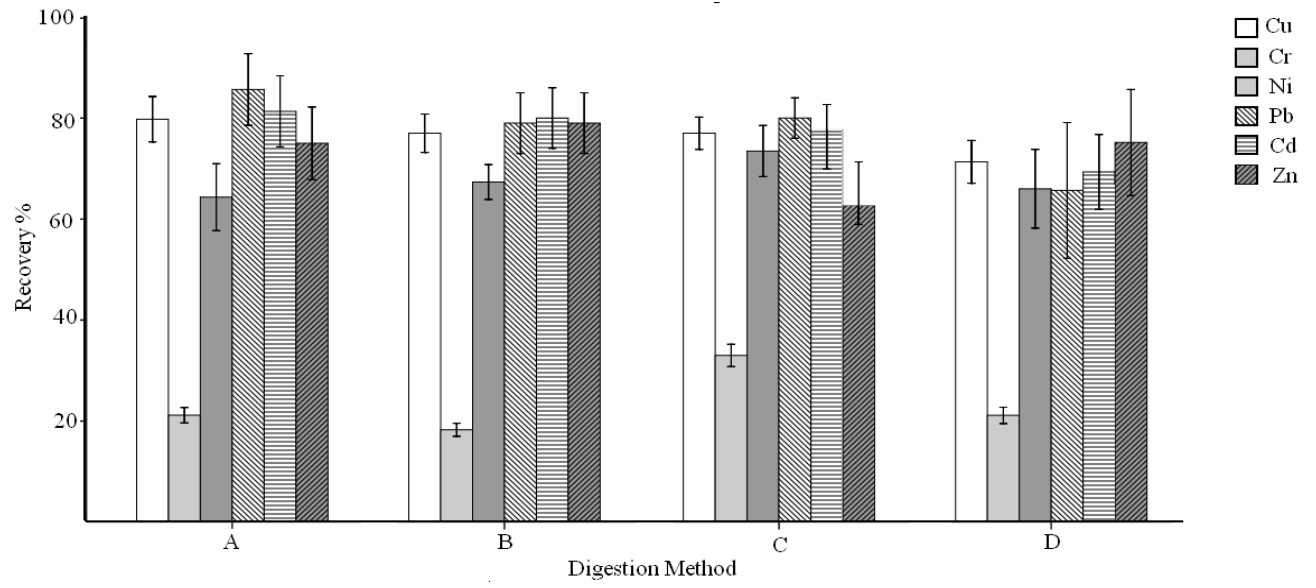


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449 Figure 3: Water soluble chlorine content per ash type

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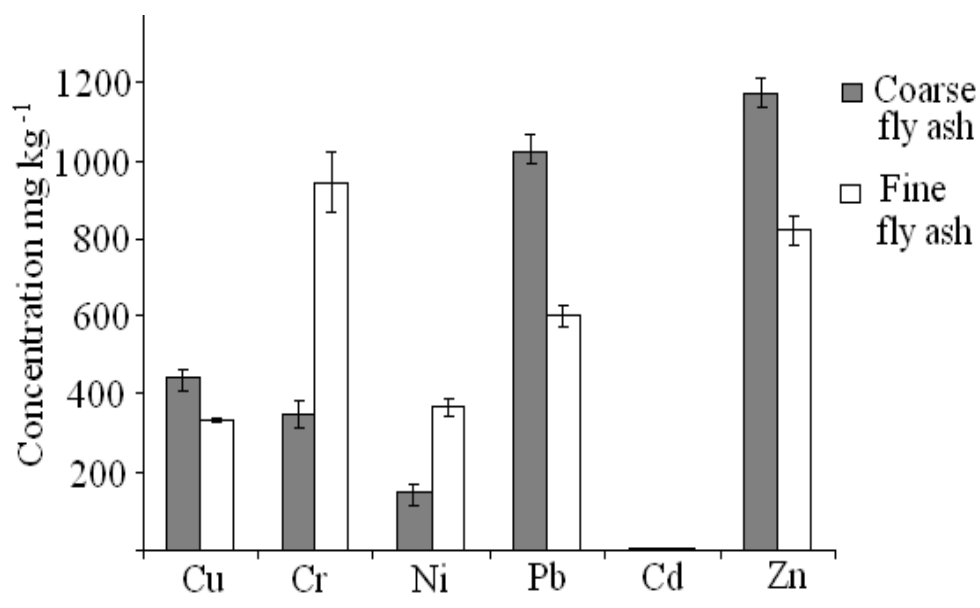
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452 Figure 4: Recoveries of metals from CRM between different MWAD methods (error
 453 bars indicate minimum and maximum values, n=7)

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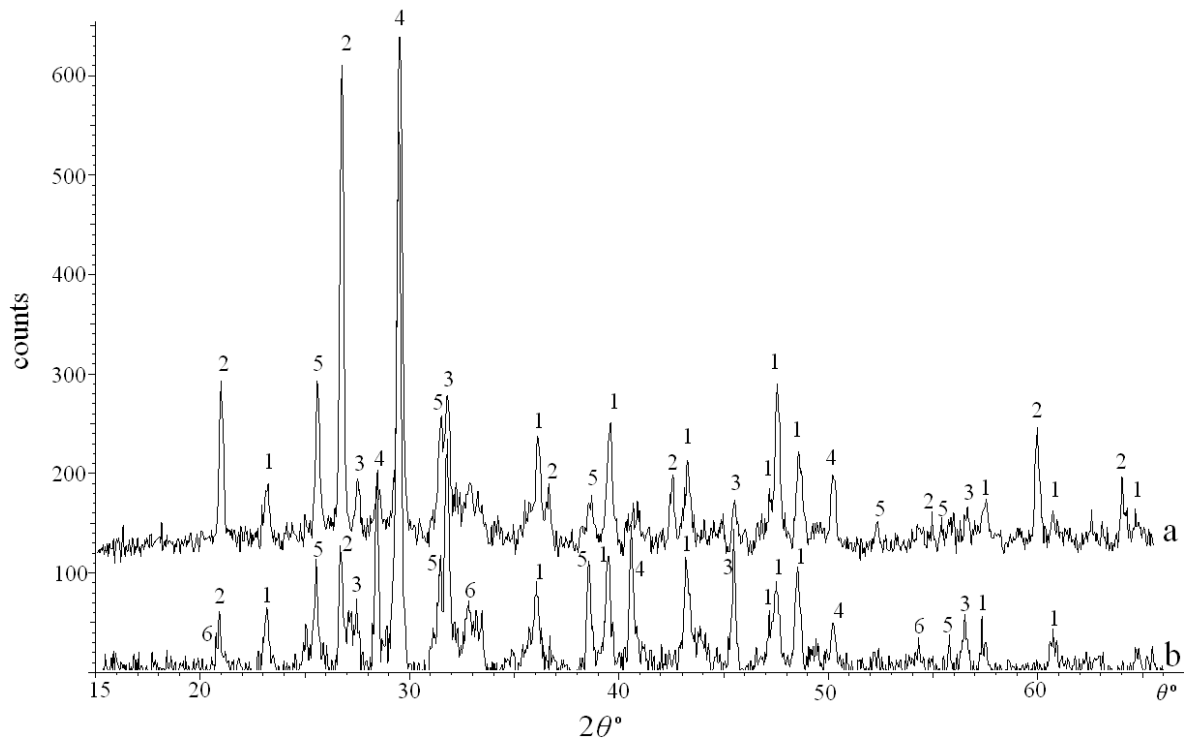
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456 Figure 5: Concentration of metals in SRF coarse and fine fly ash (error bars indicate
457 minimum and maximum values, n=7)
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460 Figure 6. X-ray diffractograms (a) coarse, (b) fine fly ash. Crystal phases recognised:
 461 1. Calcite; 2. Quartz; 3. Halite; 4. Sylvite; 5. Calcium sulphate; 6. Calcium silicate

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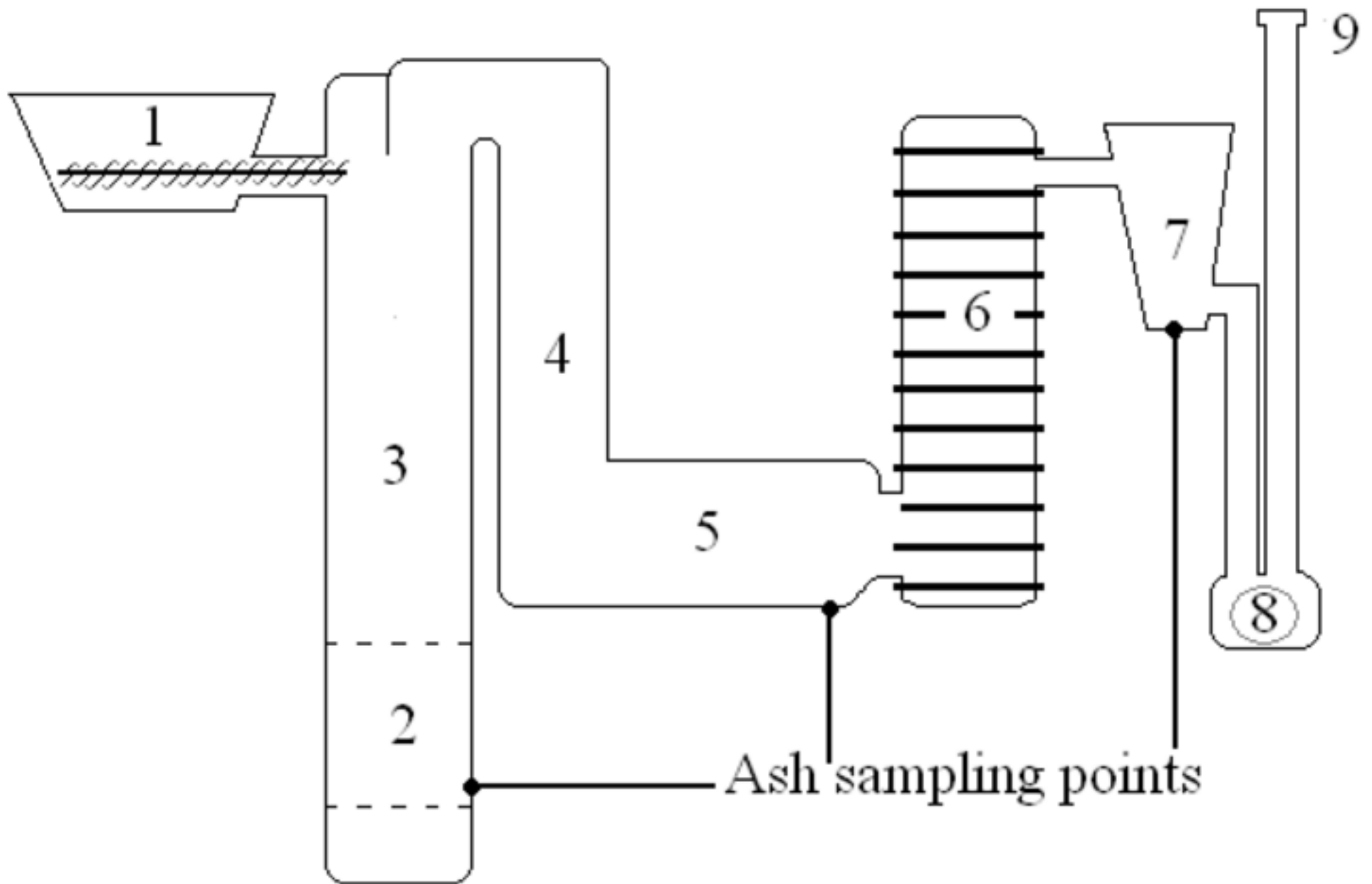


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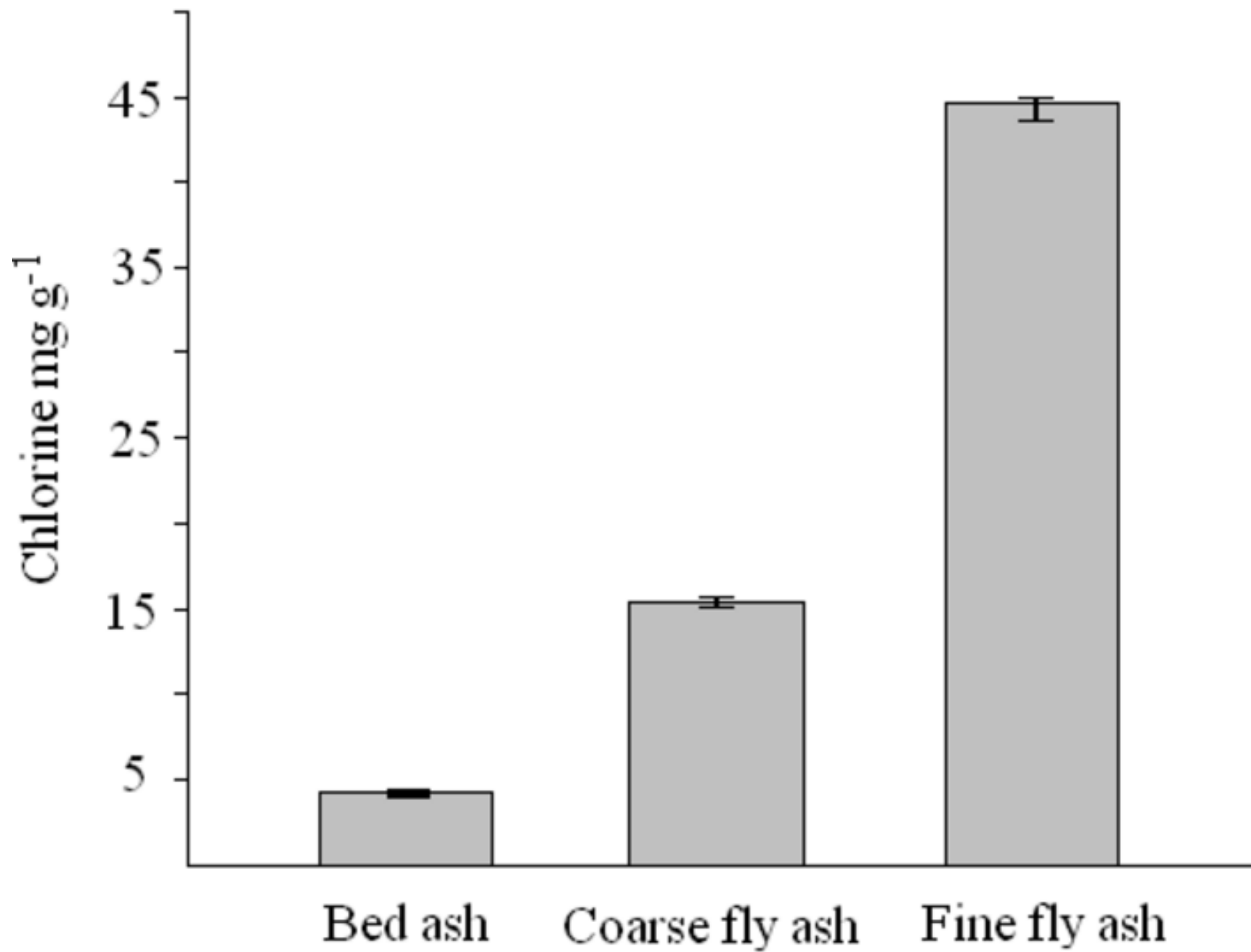


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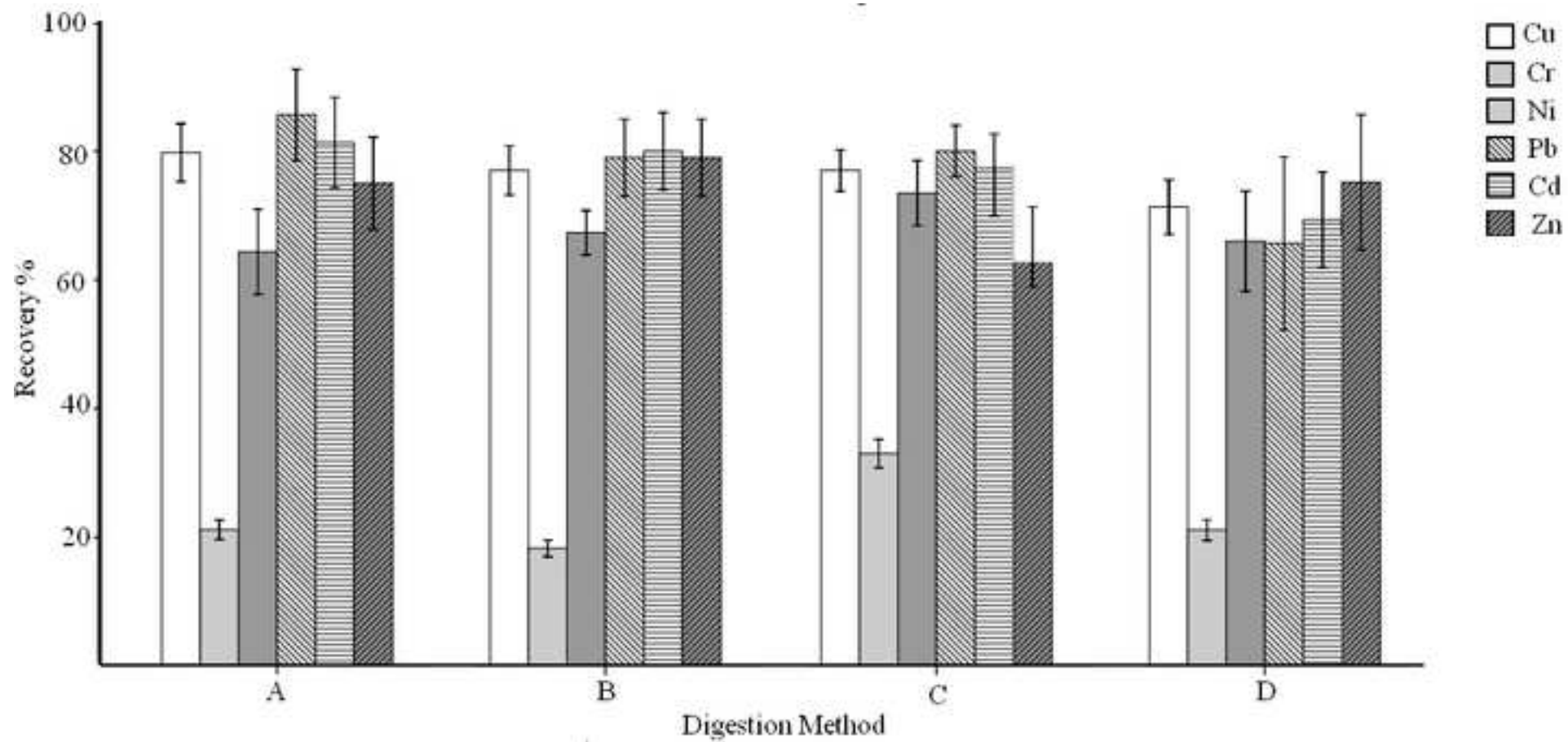
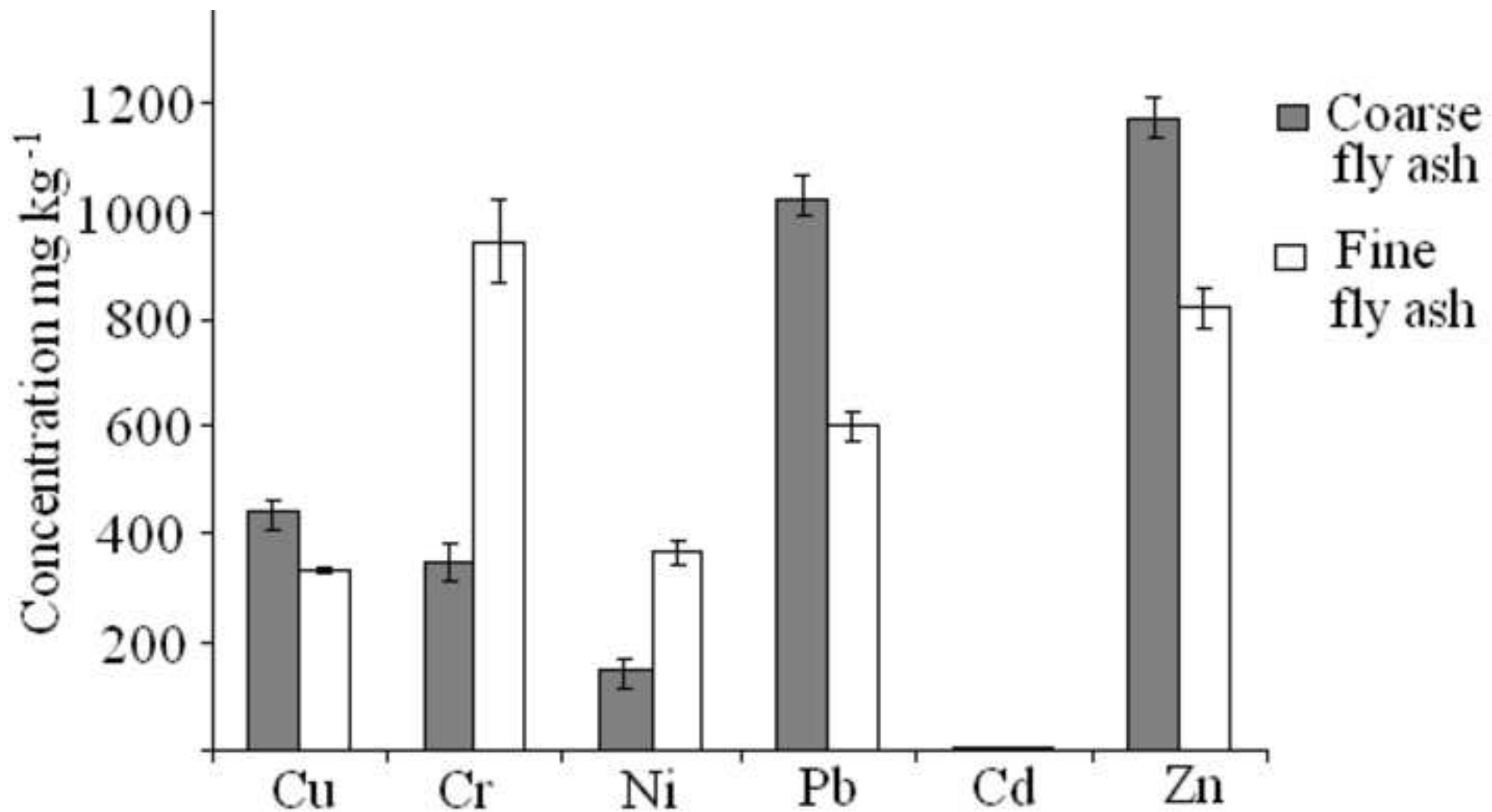


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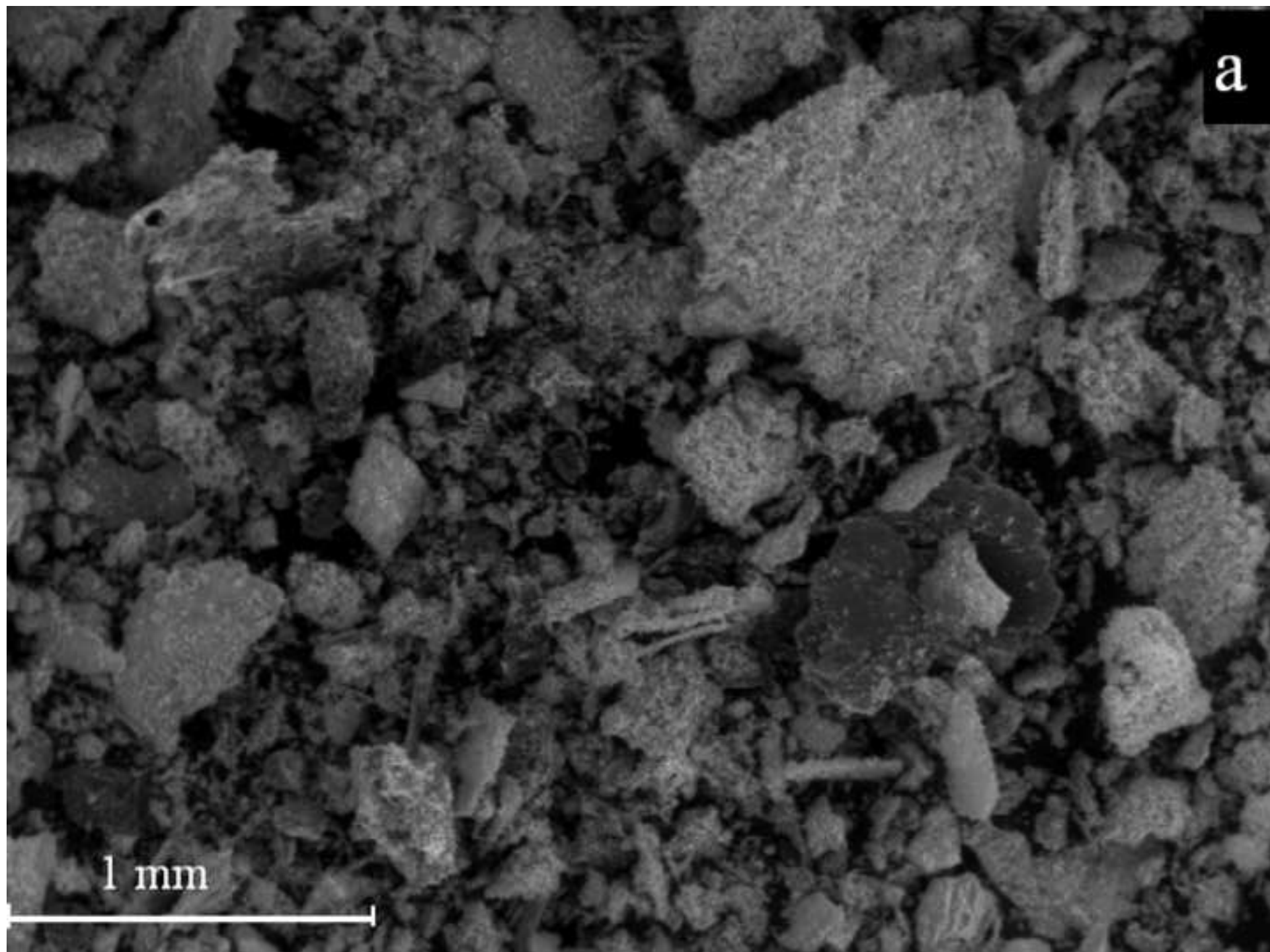
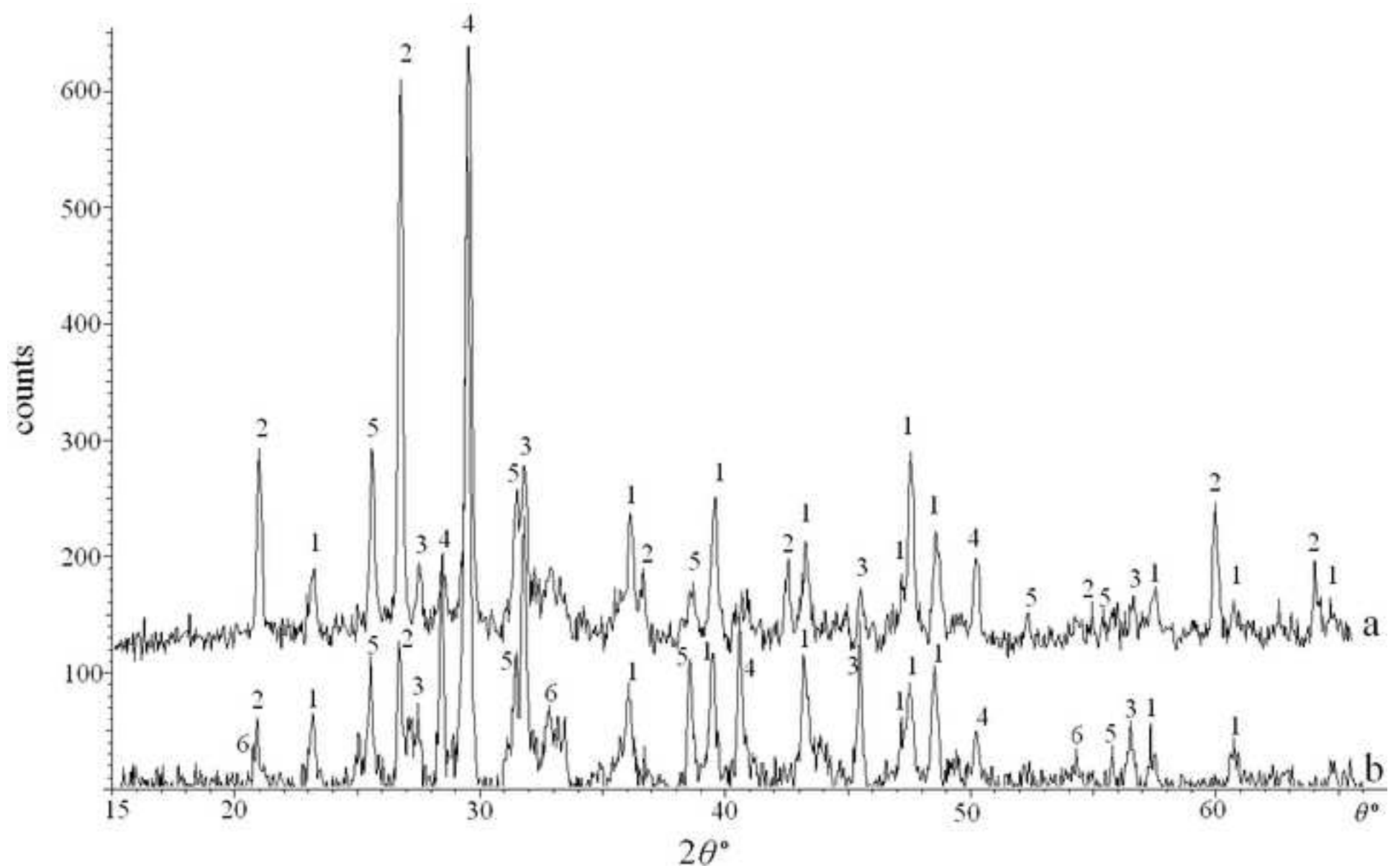


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