

1 **Bioavailability of nutrients and harmful elements in ash fertilizers: effect of granulation**

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12

13 Abstract

14

15 Environmental policies of the European Union (EU) aim to increase the amount of renewable energy
16 and to improve the use of waste streams. This will increase the amount of fly ash (FA) from biomass
17 combustion, thereby increasing the need for its utilization. Biomass FA is a good fertilizer since it
18 contains most of the nutrients that plants need. Sequential leaching would provide a more accurate
19 assessment of the potential bioavailability of the harmful elements and nutrients than the pseudo-total
20 and/or water-soluble concentration analysis that EU environmental legislation typically requires. This
21 study investigated the effect of granulation and ammonium sulfate addition on the solubility and
22 bioavailability of nutrients and harmful elements from peat and wood co-combustion FA by using
23 sequential leaching and pseudo-total acid digestion. The recoveries of the easily bioavailable nutrients
24 Ca, K, Mg, P, and S as well as the total bioavailability of Ca, K, Mg, and S reduced significantly after

25 granulation. Therefore, granulation reduced the fertilizing effect of FA. The pseudo-total recovery of
26 Ca, Mg, and S reduced after granulation, indicating that these types of FA form some very stable
27 silicate compounds besides the common self-hardening products. Ammonium sulfate addition
28 increased the recoveries of the easily bioavailable nutrients and total bioavailability recoveries of the
29 Ca, K, and Mg back to the same levels as those in FA. The total bioavailability of the harmful elements
30 As, Cd, Cr, Cu, Ni, Pb, and Zn was very low, and this does not limit the usability of FA as a fertilizer.

31
32 **Keywords:** Fly ash; Granulation; Fertilizers; Leaching; Waste utilization

34 **1. Introduction**

35
36 One of the main priorities of the EU growth strategy (Europa 2020) is sustainability, which forms the
37 basis of a low-carbon economy [1]. A low-carbon economy is achieved through reductions in
38 greenhouse gas emissions and increases in both renewable energy sources and energy efficiency. The
39 aims of the EU circular economy strategy are to increase recycling and re-use of products and waste
40 materials [2]. The EU Waste Framework Directive (2008/98/EC) [3] includes a 5-step waste hierarchy,
41 which describes the different options available for dealing with the waste. The first goal of the waste
42 hierarchy is the prevention of waste streams. If this is not possible, the next step down the hierarchy is
43 the preparation of waste for re-use, followed by recycling and other recovery (e.g., energy recovery),
44 and finally, if none of the initial 4 steps are feasible, waste should be disposed of by ecologically
45 beneficial methods.

46 The forest and power industries produce large amounts of fly ash (FA) every year in Europe. A
47 large part of this ash ends up at waste disposal sites, even though it could be productively utilized.
48 Changes to the legislation, the Europa 2020 growth strategy, and the EU circular economy strategy

49 have increased the need to utilize different combustion ashes. The most natural way to utilize biomass-
50 based FA is to use it as a fertilizer or soil amendment. In particular, wood FA contains all the
51 macronutrients plants need in almost the correct proportions, excluding nitrogen (N), which is released
52 into the atmosphere during combustion [4]. In peatlands, nitrogen levels are usually naturally high,
53 whereas phosphorous (P) and potassium (K) are the growth-limiting nutrients. Therefore, FA has great
54 potential as fertilizers for use in peatland forests. It has in fact been shown that FA can outperform
55 commercial PK fertilizers for improving tree growth [5] as well as the financial performance of forest
56 management on peatlands [6].

57 In Finland, to prevent dust problems, FA has to be granulated before application on fields or
58 forests. Granulation is known to be a significantly more cost-effective alternative for ash recycling
59 compared with unprocessed FA mainly due to improved logistics [7]. Co-granulation of FA with some
60 nitrogen containing material such as hygienized sewage sludge could produce new fertilizer products to
61 nitrogen poor soils [8].

62 The EU environmental legislation typically requires that the pseudo-total concentrations (i.e.
63 acid-leachable metals that are not part of silicate matrix) and/or water-soluble concentrations of the
64 harmful elements be studied from waste and residue materials [9–12]. This does not give an accurate
65 representation of the environmental risks associated with the utilization or disposal of these materials.
66 From an environmental point of view, of utmost importance is not the total concentration in wastes and
67 other residues, but rather the ease with which the metals can be mobilized into the environment and
68 their bioavailability. The water-soluble concentration is not a sufficient measure of the environmental
69 risks because distilled or deionized water used in these tests does not represent the normal salt
70 concentration or the ionic strength of the soil solution. Further, rainwater is usually clearly acidic
71 nowadays. The water-soluble concentration measures only the instantly bioavailable fraction of the
72 contaminants and does not evaluate the potential of contaminants to become more available with time

73 [13,14]. Moreover, these procedures are not sufficient to assess the bioavailability of nutrients from
74 FA-based fertilizers. Therefore, to obtain more detailed information about the effect of environmental
75 conditions on the bioavailability and mobility of different contaminants, sequential leaching has been
76 widely used with different environmental samples over the past decades [15].

77 In the sequential leaching procedure, various types of increasingly severe chemical reagents are
78 applied to the sample; this procedure divides the total extractable metal concentration into fractions in
79 order to assess the bioavailability and the form in which the metals occur in a waste material.
80 Therefore, compared to the pseudo-total concentrations, the sum of the fractions can give a more
81 accurate assessment of the potential total bioavailability of the harmful elements. Sequential leaching
82 does not necessarily mean total decomposition, and the cumulative extractable recoveries are usually
83 clearly lower than the total concentrations.

84 In this study, the effect of granulation and ammonium sulfate addition on the solubility and
85 bioavailability of nutrients and heavy metals from peat and wood co-combustion FA was studied using
86 the sequential leaching procedure and pseudo-total acid digestion. Although granulation is a standard
87 procedure to improve the handling of FA-based fertilizers, such a study has not been implemented
88 before.

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90 **2. Materials and methods**

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92 **2.1 Raw materials and granulation**

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94 The FA used in this study was from a 96-MW thermal power plant situated in Rovaniemi, Northern
95 Finland. The power plant uses a circulating fluidized bed combustion technique. The fuels used at the
96 plant are wood and peat. The fuel ratios (dry mass) at the power plant were approximately 50% wood

97 (logging residue) and 50% peat. The sample was collected 14.5.2014 directly from ash silo.
98 Commercial 350 g · L⁻¹ ammonium sulfate solution (Envor, Finland) was used in the granulation
99 process of granule FAGR2 (see below).

100 The compositions and sample names of the FA granules used in this study are presented in Table
101 1. For each granule type, a few kilograms were produced. Granule FAGR1 contained only FA and
102 water, whereas granule FAGR2 also contained ammonium sulfate solution. While agitating the FA
103 using a ribbon blade agitator, water (and ammonium sulfate solution) was slowly added to the FA until
104 small aggregates started to form in the paste. The pastes were granulated using a simple pan granulator.
105 A very strong odor of ammonia was observed during FAGR2 granulation. The granules were cured in a
106 hot air oven at 50 ± 2 °C for 24 h and stored at room temperature (21 °C).

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108 **Table 1.** Composition and sample names of the FA granules.

Sample	FA mass fraction (%)	Water mass fraction (%)	Ammonium sulfate mass fraction (%)
FAGR1	60	40	-
FAGR2	66	28	6

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110 **2.2 Sequential leaching procedure**

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112 The pseudo-total element concentrations were characterized by aqua regia digestion according to
113 standard ISO 11466 [16] and analyzed with the ICP-OES technique. The 4-step sequential leaching
114 procedure used in this study is presented in Table 2. This procedure is based on the Community Bureau
115 of Reference (BCR) procedure [17]. Stages 2 to 4 follow the BCR procedure, but the first stage
116 involves extraction with deionized water acidified to pH 4 with HNO₃ [18]. The purpose of the first
117 stage is to simulate the effect of acidic rainwater – present day rain – on the solubility of the metals.

118 This 4-step sequential leaching procedure has been used successfully with samples including bottom
119 ash and FA [18–21].

120 The sample mortars were first crushed and sieved to particle sizes smaller than 0.5 mm. The
121 eluates from each step were separated from the residue by centrifuging for 20 min (RCF = 3000) and
122 analyzed using the ICP-OES technique. Duplicate samples from each batch were analyzed, and the
123 averages were calculated. The moisture contents of the FA and the FA granules were measured
124 according to standard SFS-EN 12880 [22] by drying the samples in a hot air oven for 24 h at 105 ± 2
125 °C. The dried samples were placed in cooling desiccators and weighed. However, the samples were not
126 dried prior the sequential leaching procedure, since heat can affect the leaching of elements [23].
127 Instead, the moisture contents were taken into account as the leaching results were calculated. The
128 moisture mass fractions of the samples were low: 0.42 % for FA; 1.62 % for FAGR1; and 1.55 % for
129 FAGR2.

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142 **Table 2. 4-step sequential leaching procedure** [17,18].

Step	Fraction	Extractant	Experimental conditions
F1	Water-soluble	40 cm ³ H ₂ O at pH 4 (with HNO ₃)	16 h at 22 ± 5 °C, constant shaking
F2	Exchangeable and acid soluble	40 cm ³ HOAc 0.11 mol · L ⁻¹	16 h at 22 ± 5 °C, constant shaking
F3	Reducible	40 cm ³ NH ₂ OH·HCl 0.5 mol · L ⁻¹ at pH 1.5 (with HNO ₃)	16 h at 22 ± 5 °C, constant shaking
F4	Oxidizable	10 cm ³ H ₂ O ₂ 300 g · L ⁻¹ 10 cm ³ H ₂ O ₂ 300 g · L ⁻¹ 50 cm ³ NH ₄ OAc 1 mol · L ⁻¹ at pH 2 (with HNO ₃)	1 h at 22 ± 5 °C, occasional manual shaking, then 1 h 85 ± 2 °C. Reduce the volume to less than 3 cm ³ 1 h at 85 ± 2 °C 16 h at 22 ± 5 °C

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144 The fractions of the 4-step sequential leaching are the water-soluble fraction; exchangeable and acid-
 145 soluble fraction; reducible fraction; and oxidizable fraction [15]. In theory, the first fraction should
 146 contain water-soluble ions. This fraction is the most mobile, and it contains potentially the most readily
 147 available metal and metalloid species. The second fraction should contain metals bonded
 148 electrostatically, metals bonded with weak covalent bonds, or metals bonded to carbonates. The third
 149 fraction should contain metals bonded to Mn and Fe oxides, and the fourth fraction metals bonded to
 150 organic matter or to different sulfides and oxides. However, it should be noted that sequential leaching
 151 was originally designed for fractionating of sediments. Therefore, the bonding of different metals
 152 originating from matrixes that differ notably from sediments, such as FA, cannot be deduced precisely
 153 from the sequential leaching results. For example, FA is quite basic, and the acetic acid used in the
 154 second step of sequential leaching is not strong enough to acidify the sample matrix. Thus, even if the
 155 FA matrix contained some carbonates, they would not dissolve. Furthermore, the reagents used in the

156 sequential leaching are not completely target specific. However, even when the bonding of metals
157 cannot be deduced from sequential leaching data, it still gives a good estimate of the solubility of
158 metals in real environmental conditions. In the present study, the first two fractions (F1 and F2) are
159 referred to as easily bioavailable fractions. The total bioavailability refers to the sum of the fractions
160 (F1–F4) [15,17,24]. Recovery % of a particular element E was calculated with equation 1:

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$$162 \text{ Recovery \%} = (x(E)_{\text{FAGRi}}/x(E)_{\text{FA}}) \cdot 100 \quad (1)$$

163 where x = content in $\text{mg} \cdot \text{kg}^{-1}$.

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165 **3. Results and discussion**

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167 **3.1 Contents and leaching of nutrients**

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169 The pseudo-total contents of nutrients Ca, K, Mg, P, and S are presented in Table 3. FA and the
170 granules FAGR1 and FAGR2 contained plenty of Ca and a lesser degree of the other nutrients.
171 Granulation had a clear effect on the recoveries of Ca (81.5 %), Mg (77.4 %), and S (65.8 %) from
172 FAGR1. However, the recoveries of the main nutrients K and P were the same before and after
173 granulation. The addition of ammonium sulfate to FAGR2 increased the recoveries of Ca (104.9 %),
174 Mg (102.6 %) and S (104.4 %) back to the same levels as those in FA. The Ca content and the K + P
175 content exceeded the minimum requirements of Finnish Fertilizer Product Decree 24/2011 [10] for
176 forest fertilizers.

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180 **Table 3.** Pseudo-total contents of nutrients Ca, K, Mg, P, and S and the limit values of Finnish
 181 Fertilizer Product Decree 24/2011 [10].

	Ca (g · kg ⁻¹)	K (g · kg ⁻¹)	P (g · kg ⁻¹)	Mg (g · kg ⁻¹)	S (g · kg ⁻¹)
FA	103	7.95	9.92	19.0	12.0
FAGR1	83.9	8.05	9.97	14.7	7.89
<i>Recovery %¹</i>	<i>81.5</i>	<i>101.3</i>	<i>100.5</i>	<i>77.4</i>	<i>65.8</i>
FAGR2	108	7.98	9.90	19.5	19.0
<i>Recovery %¹</i>	<i>104.9</i>	<i>100.4</i>	<i>99.8</i>	<i>102.6</i>	<i>104.4²</i>
Limit value	≥ 60	K + P ≥ 20			

¹*Recovery %* = $(x(E)_{\text{FAGRi}}/x(E)_{\text{FA}}) \cdot 100$, where $x(E)$ = content of a particular element E in mg · kg⁻¹.

²Actual recovery based on original S (12.0 g · kg⁻¹) and added S (6.2 g · kg⁻¹) contents.

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183 The total bioavailability ($\sum F_i$) and the amounts of easily bioavailable (F1 + F2) nutrients Ca, K, Mg, P,
 184 and S are presented in Table 4. The results show that granulation had a significant effect on the
 185 recoveries of the easily bioavailable Ca (67.9 %), K (47.5 %), Mg (46.7 %), P (34.1 %), and S (59.0 %)
 186 from FAGR1 (Table 4). In practice, this means that the quick-acting fertilizer effect of granulated ash
 187 FAGR1 is smaller than that of the FA. In addition, the total bioavailability recoveries of Ca (74.1 %), K
 188 (83.6 %), Mg (54.3 %), and S (59.9 %) decreased after granulation. However, the total bioavailability
 189 recovery of P (130.6 %) from FAGR1 increased after granulation

190 The addition of ammonium sulfate increased the recoveries of easily bioavailable Ca (99.2 %), K (96.2
 191 %), Mg (104.0 %) and S (100.6 %) from FAGR2 back to the same levels as those in FA. The same was
 192 observed for the total bioavailability recoveries of these elements (Ca 100.9 %; K 97.1 %; Mg 103.4 %;
 193 and S 102.9 %). The recovery of easily bioavailable P (5.6 %) from FAGR2 decreased by 95 %
 194 compared to that in the case of FA. This decrease in easily bioavailable P could be a desirable property
 195 for a granule, especially in the case of an agricultural fertilizer. This is because easily bioavailable P
 196 can leach from fields into surface waters causing eutrophication (leading to algal blooms) in nearby

197 rivers and lakes. The ammonium sulfate addition to FAGR2 did not have an impact on the recovery of
198 P (136.3 %) compared to FAGR1.

199 Based on the sequential leaching results, Ca, K, Mg, and S are not only physically encapsulated
200 to the granulated FA but they are instead chemically bonded to the matrix. This behavior was expected
201 especially for Ca and S, since they are the key elements in the self-hardening of ash. Self-hardening
202 begins as calcium oxide (CaO) reacts with water instantly to form calcium hydroxide (Ca(OH)₂) in an
203 exothermic reaction [25]:

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207 Ca(OH)₂ gradually reacts with CO₂ to form calcium carbonate (CaCO₃) [25]:

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211 Carbonation reaction (2) is considered to be the main strength-providing reaction in the self-hardening
212 of ash. Ca also forms other strength-providing products, such as ettringite (Ca₆Al₂(SO₄)₃(OH)₁₂·26H₂O)
213 or gypsum (CaSO₄·2H₂O) if Al and/or S are available [26]:

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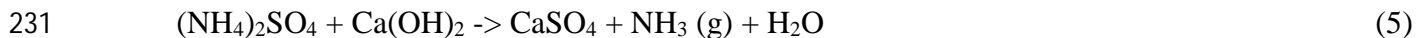
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218 Another earth-alkali metal, Mg, reacts similarly to Ca during self-hardening, which explains the
219 reduced solubility of Mg. Ettringite is only stable at high pH values [27], and all other self-hardening

220 products dissolve during sequential leaching procedure. It is therefore surprising that the total
221 bioavailabilities as well as the pseudo-total recoveries of Ca, Mg, and S decreased owing to
222 granulation. This means that these elements also form other, more stable, phases during self-hardening.
223 In fact, Ohenoja et al. [28] studied the self-hardening of peat and wood FA from fluidized bed
224 combustion and discovered that the amount of reactive SiO₂ had a clear correlation with the
225 compressive strength of self-hardened FA. It is therefore most likely that these types of FA also form
226 some stable silicate compounds, which would explain the reduced solubility to aqua regia.

227 A very strong odor of ammonia was observed during FAGR2 granulation as ammonium sulfate
228 solution was added to the mixture. It was later discovered that during granulation of FA, the
229 ammonium sulfate ((NH₄)₂SO₄) reacts with Ca(OH)₂ as follows [29]:

230



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233 Calcium sulfate (CaSO₄) and ammonia (NH₃) gas are formed in the reaction. In practice, ammonium
234 cannot be added to ash granules this way owing to the reaction with hydroxides and there could even be
235 potential health risks due to the release of ammonia gas. The increase in the pseudo-total content of Ca
236 was higher than the expected increase due to ammonium sulfate addition. It is therefore likely that
237 ammonium sulfate addition hinders some Ca reactions, which causes the increase in the solubility of
238 Ca.

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243 **Table 4.** Amounts of easily bioavailable fractions and total bioavailability of nutrients Ca, K, Mg, P,
 244 and S.

	Ca (g · kg ⁻¹)	K (g · kg ⁻¹)	Mg (g · kg ⁻¹)	P (g · kg ⁻¹)	S (g · kg ⁻¹)
FA					
Easily bioavailable (F1 + F2)	53.0	1.83	5.76	0.323	11.0
Total bioavailability (F1 + F2 + F3 + F4)	81.6	3.73	7.26	4.02	11.5
FAGR1					
Easily bioavailable (F1 + F2)	36.0	0.87	2.69	0.110	6.49
<i>Recovery %¹</i>	<i>67.9</i>	<i>47.5</i>	<i>46.7</i>	<i>34.1</i>	<i>59.0</i>
Total bioavailability (F1 + F2 + F3 + F4)	60.5	3.12	3.94	5.24	6.89
<i>Recovery %¹</i>	<i>74.1</i>	<i>83.6</i>	<i>54.3</i>	<i>130.3</i>	<i>59.9</i>
FAGR2					
Easily bioavailable (F1 + F2)	52.6	1.76	5.99	0.018	17.3
<i>Recovery %¹</i>	<i>99.2</i>	<i>96.2</i>	<i>104.0</i>	<i>5.6</i>	<i>100.6</i>
Total bioavailability (F1 + F2 + F3 + F4)	82.3	3.62	7.51	5.48	17.7
<i>Recovery %¹</i>	<i>100.9</i>	<i>97.1</i>	<i>103.4</i>	<i>136.3</i>	<i>102.9²</i>

¹*Recovery %* = $(x(E)_{\text{FAGR1}}/x(E)_{\text{FA}}) \cdot 100$, where $x(E)$ = content of a particular element E in mg · kg⁻¹.

²Actual recovery based on original S (12.0 g · kg⁻¹) and added S (6.2 g · kg⁻¹) contents.

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246 3.2 Contents and leaching of harmful elements

247

248 The pseudo-total contents of the harmful metals As, Cd, Cr, Cu, Ni, Pb and Zn are presented in Table
 249 5. The pseudo-total contents of all the harmful metals were small and they were clearly below the limit
 250 values of Finnish Fertilizer Product Decree 24/2011 [10] for forest fertilizers. The recoveries of As
 251 (72.0 %), Cd (73.7 %), and Cu (87.4 %) were smaller from the FAGR1 than from FA, but the
 252 recoveries of Cr (95.7 %), Ni (92.2 %), Pb (106.5 %), and Zn (95.1 %) were roughly the same before

253 and after granulation. Ammonium sulfate addition increased the recoveries of As (108.0 %), Cd (105.3
 254 %), and Cu (102.9 %) from FAGR2 back to the same levels as those in the FA.

255

256 **Table 5.** Pseudo-total contents of harmful metals As, Cd, Cr, Cu, Ni, Pb, and Zn and the limit values of
 257 Finnish Fertilizer Product Decree 24/2011 [10].

	As (mg · kg ⁻¹)	Cd (mg · kg ⁻¹)	Cr (mg · kg ⁻¹)	Cu (mg · kg ⁻¹)	Ni (mg · kg ⁻¹)	Pb (mg · kg ⁻¹)	Zn (mg · kg ⁻¹)
FA	25	1.9	69	87	51	31	284
FAGR1	18	1.4	66	76	47	33	270
<i>Recovery %¹</i>	<i>72.0</i>	<i>73.7</i>	<i>95.7</i>	<i>87.4</i>	<i>92.2</i>	<i>106.5</i>	<i>95.1</i>
FAGR2	27	2.0	71	91	52	31	300
<i>Recovery %¹</i>	<i>108.0</i>	<i>105.3</i>	<i>102.9</i>	<i>104.6</i>	<i>102.0</i>	<i>100.0</i>	<i>111.1</i>
Limit value	25/40	2.5/25	300/300	600/700	100/150	100/150	1500/4500
Field/forest fertilizers							

¹*Recovery %* = $(x(E)_{\text{FAGRi}}/x(E)_{\text{FA}}) \cdot 100$, where $x(E)$ = content of a particular element E in mg · kg⁻¹.

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259 Sequential leaching results of harmful metals As, Cd, Cr, Cu, Ni, Pb, and Zn are presented in Table 6.

260 The amounts of water-soluble fraction F1 were mostly below the determination limits, and the total
 261 bioavailabilities were small. Therefore, a comparison between FA and granules FAGR1 and FAGR2 is
 262 not meaningful. However, the total bioavailability recoveries of Zn (58.2 %) and Cr (82.9 %) from the
 263 FAGR1 decreased owing to granulation. The recoveries of both Zn (115 %) and Cr (102 %) increased
 264 after ammonium sulfate addition to FAGR2. When the pseudo-total contents (Table 5) and sequential
 265 leaching data (Table 6) are compared, it is found that most of the harmful metals dissolve only with
 266 aqua regia digestion, and therefore, the aqua regia digestion is a poor estimate of the bioavailability of

267 these metals. In practice, the total bioavailability of these metals is very low, and this does not limit the
 268 usability of FA as a fertilizer in agriculture or forestry.

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270 **Table 6.** Sequential leaching results of harmful metals As, Cd, Cr, Cu, Ni, Pb, and Zn.

	As (mg · kg ⁻¹)	Cd (mg · kg ⁻¹)	Cr (mg · kg ⁻¹)	Cu (mg · kg ⁻¹)	Ni (mg · kg ⁻¹)	Pb (mg · kg ⁻¹)	Zn (mg · kg ⁻¹)
FA							
F1	<1.2	<0.04	0.8	<0.1	<0.1	<0.4	0.1
F2	<1.2	0.50	1.1	2.3	2.7	0.6	33
F3	3.7	0.38	1.7	7.2	0.8	4.4	31
F4	<1.5	0.06	1.4	2.5	0.5	2.4	5
FAGR1							
F1	<1.2	<0.04	0.4	<0.1	<0.1	<0.4	0.1
F2	<1.2	0.41	0.9	2.9	2.7	0.9	19
F3	5.2	0.33	1.8	7.3	0.9	9	18
F4	<1.5	<0.05	1	2.5	0.3	3.5	3.1
FAGR2							
F1	<1.2	<0.04	0.6	<0.1	<0.1	<0.4	0.04
F2	<1.2	0.54	0.6	2	2.5	0.7	44
F3	6.8	0.41	1.9	8	1	5.7	31
F4	1.7	0.08	2	3.4	0.7	3.7	4.4

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272 4. Conclusions

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274 A sequential leaching procedure and pseudo-total acid digestion were used to investigate the effect of
 275 granulation and ammonium sulfate addition on the solubility and bioavailability of nutrients and
 276 harmful elements in peat and wood co-combustion FA. Results indicated that granulation significantly
 277 reduced the recoveries of the easily bioavailable nutrients Ca, K, Mg, P, and S. This means that
 278 granulation reduces the quick-acting fertilizer effect of FA. Results also indicated that the total
 279 bioavailability of Ca, K, Mg, and S reduced after granulation. Therefore, the fertilizing effect of FA

280 reduces after granulation. Owing to the reduced pseudo-total recovery of Ca, Mg, and S after
281 granulation, it is most likely that these types of FA also form some very stable silicate compounds
282 besides the common self-hardening products. Addition of ammonium sulfate increases the recoveries
283 of easily bioavailable nutrients and the total bioavailability recoveries of the Ca, K, and Mg back on the
284 same levels as those in FA, and the recoveries of S are increased owing to the increased sulfate content.
285 The sequential leaching results indicate that the total bioavailability of the harmful elements As, Cd,
286 Cr, Cu, Ni, Pb, and Zn is very low, and this does not limit the usability of FA as a fertilizer in
287 agriculture or forestry.

288

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290

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296

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