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1 Influence of pyrolysis temperature and production unit on formation of
2 selected PAHs, oxy-PAHs, N-PACs, PCDDs, and PCDFs in biochar – A
3 screening study

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14 **Abstract**

15 The influence of reactor type and operating conditions of the pyrolysis unit on the final concentration of
16 toxic contaminants in biochar remains unclear. Therefore, we determined the concentrations of polycyclic
17 aromatic hydrocarbons (PAHs), oxygenated polycyclic aromatic hydrocarbons (oxy-PAHs), nitrogen-
18 containing polycyclic aromatic compounds (N-PACs), polychlorinated dibenzo-*p*-dioxins (PCDDs), and
19 dibenzofurans (PCDFs) in biochars produced from three different feedstocks (softwood, wheat straw, and
20 anaerobic digestate). Different-scaled pyrolysis units (one batch and two continuous units) at two different
21 temperatures (550 °C and 700 °C) were considered. The results revealed that the type of biomass had a
22 significant influence on the PAH, oxy-PAH, and N-PAC content of the biochars. The configuration and type
23 of the pyrolysis unit influenced only the wheat straw pyrolyzed at 550 °C. PCDDs and PCDFs occurred at very
24 low levels in the biochars. In terms of PAH, PCDD, and PCDF content, the biochars assessed in this study
25 represent a low risk to the environment, regardless of the temperature and type and size of the pyrolysis
26 unit.

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32 **Keywords**

33 Polychlorinated dibenzo-*p*-dioxin; polychlorinated dibenzofuran; polycyclic aromatic hydrocarbons;
34 oxygenated polycyclic aromatic hydrocarbons; nitrogen-containing polycyclic aromatic compounds.

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41 Introduction

42 During pyrolysis, materials undergo thermochemical decomposition at temperatures above 300 °C in an
43 oxygen-limited environment. The yield and chemical composition of the resulting pyrolysis products vary
44 with the characteristics of the feedstock and the process variables, e.g., heating rate and residence time of
45 the process (Mohan et al. 2006; Zhao et al. 2013). To date, the liquid and gas fraction has been the most
46 analyzed pyrolysis product. However, biochar from lignocellulosic biomass has gained significant attention
47 due to its properties and potential use in environmental and agricultural applications (e.g. as soil
48 amendment and replacement for or supplement to activated carbon (Lehman and Joseph 2009)).

49 Thermal decomposition of biomass yields a complex mixture of condensable hydrocarbons, i.e. tar, which
50 consists of single- to five-ring aromatics, phenolic compounds, and complex polycyclic aromatic
51 hydrocarbons (PAHs) (Wolfesberger et al. 2009). The tar-like products are highly branched at moderate
52 temperatures (~500 °C) (Pakdel and Roy 1991), but (in general) highly condensed and less oxygenated at
53 high temperatures (>700 °C) (Elliott 1986; Baker and Elliott 1986). Oxygenated-PAHs (oxy-PAHs) and
54 nitrogen-containing heterocyclic polycyclic aromatic compounds (N-PACs), which typically occur as PAH co-
55 pollutants in soils and groundwater (Lundstedt et al. 2003; Arp et al. 2014), display similar toxicity to PAHs
56 (Andersson et al. 2015). Therefore, oxy-PAHs should be considered for inclusion in biochar regulations. Oxy-
57 PAHs may form through either biological, chemical or photo-oxidation (Andersson et al. 2015) or catalytic
58 transformation of PAHs (Nielsen 1999), whereas N-PACs form via pyrolysis of lignocellulose materials and
59 sewage (Britt et al. 2002). N-PACs have been reported from the pyrolysis of sewage sludge (Fullana et al.
60 2003) During thermochemical processes, PAHs (Weber et al. 2001) and oxy-PAHs (Hajizadeh et al. 2011)
61 may also act as precursors for the formation of chlorinated aromatics, such as polychlorinated dibenzo-*p*-
62 dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs).

63 Biochar intended for soil application must fulfill certain property- and composition-related requirements,
64 to prevent harm to the ecosystem (Buss and Mašek 2014). Therefore, several guidelines with suggested
65 threshold values for contaminants (including PAHs, PCDDs or PCDFs) in biochar have been established, and
66 the importance of contaminant analysis has been emphasized (British Biochar Foundation 2014;
67 International Biochar Initiative 2015; European Biochar Foundation 2016).

68 Biochars with low concentration of contaminants may be achieved by selecting suitable feedstocks and
69 controlling the operating conditions in the pyrolysis unit. Therefore, knowledge of the variation in different
70 process variables associated with different pyrolysis units is essential for producing high-quality biochar.
71 However, a relationship between the pyrolysis temperature and the concentration of PAH in biochar

72 remains elusive (Freddo et al. 2012; Hale et al. 2012; Kloss et al. 2012; Devi et al. 2015). Buss et al. (2016-a)
73 have attributed this to a simultaneous increase in PAH formation and evaporation from the biochar with
74 increasing temperature. The influence of the scale, reactor type, and configuration of the pyrolysis unit on
75 the PAH concentration of the biochar remains unclear. In addition, the concentration of chlorinated
76 organics in biochar has rarely been assessed (Hale et al. 2012; Wiedner et al. 2013), and to the best of our
77 knowledge the concentrations of oxy-PAH and N-PAC in biochars have yet to be reported.

78 In this study, we evaluate organic contaminants (PCDD, PCDF, PAH, oxy-PAH, and N-PAC) found in biochars
79 from different biomass materials treated in different types of pyrolysis units. Three different feedstocks
80 (softwood pellets, wheat straw pellets, and anaerobic digestate) were pyrolyzed at two different
81 temperatures (550 °C and 700 °C), using three pyrolysis setups (one batch and two continuous units) of
82 different scales.

83

84 **Materials and methods**

85 **Feedstocks**

86 The biochars were produced from three different types of biomass: commercial softwood (pine and spruce)
87 pellets (Premium Puffin, Puffin Pellets); commercial wheat straw pellets (Agripellets Ltd.), and anaerobically
88 digested sewage sludge (AD) from water-treatment works. The characterization of these feedstocks,
89 proximate and ultimate analysis, are shown in Table 1.

90

91 **Pyrolysis experiments**

92 The pyrolysis experiments were conducted in three different pyrolysis reactors (one batch reactor and two
93 continuous reactors) located at the UK Biochar Research Centre (UKBRC), University of Edinburgh. Key
94 characteristics of the units are presented in Table 2 and further details can be found in the referenced
95 articles.

96 An overview of the performed pyrolysis experiments and the collected samples is provided in Table 3. In
97 the two continuous reactors (Stage II (Buss et al. 2016-b) and III (Buss and Mašek 2014)), mean residence
98 times of 20 min were applied for all materials. The residence time was estimated by establishing first the
99 temperature profile of the biomass/char bed along the rotary kiln reactor (Stage III, Table 2) as well as the
100 residence time distribution of particles in the reactor. Based on this information, the corresponding heating
101 rate experienced by particles in the reactor and their residence time at the peak temperature were
102 calculated. Therefore, while the mean residence time of particles in continuous reactor was 20 minutes, the

103 residence time at peak temperature was only between 5–10 minutes, depending on the material used.
104 Thus, obtained parameters were then used as settings in the batch reactor to reproduce the conditions in
105 the continuous pyrolysis unit as closely as possible. In the Stage I reactor (Crombie et al., 2013), the
106 retention time at the highest treatment temperature was adapted to reflect the retention times in the
107 heated areas of the furnace of the continuous reactors. Therefore, softwood was exposed for 10 min (each)
108 to temperatures of 550 °C and 700 °C, whereas wheat straw was exposed for 5 min and 6 min, respectively.

109
110 **Sample extraction and cleanup**
111 We determined the fraction of 16 EPA priority PAHs (US EPA, 2015), eleven oxy-PAHs (Arp et al. 2014;
112 Andersson et al. 2015), four N-PACs (Arp et al. 2014), PCDDs, and PCDFs (homolog sums and WHO₂₀₀₅-TEQ
113 (Van den Berg et al. 2006)) occurring in biochars and liquid samples. The target PAHs, oxy-PAHs, and N-PACs
114 are listed in Table 4.

115 The chars were extracted, at 150 °C, via pressurized liquid extraction (Dionex 350, Thermo Fisher Scientific,
116 Waltham, USA) using toluene of analytical grade quality (Fluka, ≥99.7%), following the procedure outlined
117 by Gao et al. (2015). The liquid fraction was extracted via liquid/liquid extraction using n-hexane. For PCDD
118 and PCDF analysis, the extracts were all cleaned-up using a multi-layer silica column followed by
119 fractionation with an AX-21 carbon/celite column (see Liljelind et al. (2003) for further details of the
120 method). For analysis of PAHs, oxy-PAHs, and N-PACs in the char samples, clean-up was conducted using
121 open columns containing 5 g KOH-silica, eluted with dichloromethane. The clean extracts were
122 concentrated to ~1 mL of toluene. The liquid samples were cleaned via the same procedure, using n-hexane
123 (rather than dichloromethane) as the eluent. Further details of the method for PAH, oxy- PAH, and N-PAC
124 analysis are provided elsewhere (Arp et al. 2014). All samples were single samples.

125
126 **Instrumental analysis**
127 The analyses were all performed on a GC-HRMS – Hewlett-Packard 5890 gas chromatograph (Agilent
128 Technology, Santa Clara, USA) coupled to an Autospec Ultima Mass Spectrometer (Waters Corporation,
129 Milford, USA), using a DB5 column (60 m: length, 0.32 mm: internal diameter, 25 µm: film thickness) (Agilent
130 Technology, Santa Clara, USA). The main purpose of using HRMS was to make it possible to separate oxy-
131 PAHs from PAHs, and the method used was previously described by Arp et al. (2014). The mass
132 spectrometer was operated in electron impact ionization/selected ion-monitoring mode and analytes were
133 quantified using the isotope dilution technique. PAHs, oxy-PAHs, and N-PACs were identified by comparing

134 retention times to quantification congeners in the reference standard, while PCDD and PCDF were
135 compared with published GC-MS chromatograms (Ryan et al. 1991; Bacher et al. 1992).

136

137 QA/QC

138 All laboratory work was performed using validated methods, and laboratory blanks were extracted with the
139 samples and treated as samples (i.e., single samples) throughout the clean-up process. The reported
140 concentrations (signal-to-noise ratio: 10) were all higher than the limit of quantification (LOQ). For all
141 reported concentrations, blank concentrations were below five times sample concentrations. Due to this
142 cutoff, Acenaphthylene was removed from the reported results due to analytical uncertainties.

143

144 Results and discussion

145 PAHs in the biochars

146 The total PAH concentrations measured in the biochars varied considerably, from 0.82 to 19.6 $\mu\text{g}\cdot\text{g}_{\text{biochar}}^{-1}$,
147 and seemed to be largely influenced by the feedstock type. This is particularly striking for concentrations in
148 the three biochars produced at 550 °C (Fig. 1). For the same pyrolysis unit, the PAH concentrations of the
149 wheat straw-derived biochars were (in some cases) almost seven times higher than those obtained from
150 the softwood feedstock. The PAHs in biochars from all three feedstocks consisted mainly of two- and three-
151 ring species, regardless of the pyrolysis temperature and unit scale. Furthermore, multi-ringed species, i.e.,
152 four- to six-ringed PAHs, occurred more abundantly in the wheat straw-derived biochar than in the other
153 feedstocks. However, consistent with a previous study (Keiluweit et al. 2012), wheat straw-derived biochars
154 produced at 700°C contained higher concentrations of PAHs than those produced at 550°C. The unit size
155 had a substantial impact on PAH formation only for wheat straw pyrolyzed at 550 °C, where PAH formation
156 was positively correlated with the unit size.

157 The International Biochar Initiative (IBI) guidelines have established threshold values, 6 and 300 $\mu\text{g}\cdot\text{g}_{\text{biochar}}^{-1}$,
158 lower and upper limit respectively, for the total PAH concentration of biochar (see Fig. 1)
159 (International Biochar Initiative, 2015). The PAH concentrations of the softwood-derived biochars were all
160 less than the lower limit (6 $\mu\text{g}\cdot\text{g}_{\text{biochar}}^{-1}$), regardless of the pyrolysis temperature and the type and size of the
161 unit . All biochars produced in this study meet the IBI PAH standards, and are thereby considered safe for
162 use as soil amendments; softwood yielded the biochar with the lowest potential risk for PAH-related effects.

163

164 **Oxygenated-PAHs and N-PACs in the biochars**

165 Oxy-PAHs and N-PACs occurred at detectable levels in all biochars, but the corresponding concentrations
166 were lower than those of the PAHs (Fig. 2). The total oxy-PAH and N-PAC concentrations ranged from 34 to
167 3100 ng·g_{biochar}⁻¹ and 0.4 to 477 ng·g_{biochar}⁻¹, respectively. The oxy-PAHs and N-PACs consisted mainly of
168 three-ringed species, and slightly higher concentrations of the multi-ringed oxy-PAH species were
169 generated during wheat-straw pyrolysis than during softwood pyrolysis. As in the case of PAHs, compared
170 with the pyrolysis reactor size the feedstock exerted a larger influence on oxy-PAH formation. Furthermore,
171 the reactor size had a substantial impact only on the oxy-PAH concentration in the biochar generated from
172 wheat straw pyrolyzed at 550 °C. The highest concentration of oxy-PAH, which was more than 18 times
173 higher and almost 6 times higher than those of softwood and wheat straw, respectively, was generated
174 during Stage 1 pyrolysis (at 550 °C) of anaerobic digestate. In this case, the elevated oxy-PAH concentrations
175 are attributed to the composition of the digestate feedstock, which differs from those of the other two
176 feedstocks.

177 The highest concentration (477 ng·g_{biochar}⁻¹) of N-PACs occurred in wheat straw (rather than the anaerobic
178 digestate) pyrolyzed at 550 °C (Stage II), despite the anaerobic digestate having higher total N content than
179 the wheat straw (Table 1). This possibly indicates that not total content, but actual N speciation
180 (organic/inorganic) dictates the formation magnitude of the N-PAC species. Discussion on the toxicity of
181 oxy-PAHs and N-PACs is ongoing, and therefore threshold values for these compounds in biochar are lacking
182 (Andersson et al. 2015).

183

184 **Distribution of PAH, oxy-PAH, and N-PAC between biochar and the liquid fraction in Stage I (SI)**

185 The liquid fraction, which was only collected from Stage I (batch reactor, Table 2), constituted 44–49% of
186 the total product yield of the pyrolysis process (Table 3). The distribution of PAH, oxy-PAH, and N-PAC
187 between the biochar and liquid fraction showed that these products occurred mainly in the liquid fraction.
188 In figure Fig. 3 the concentrations of PAH and oxy-PAH is shown. For example, the PAH concentration of the
189 liquid fraction ranged from 28.6 to 351 µg·g⁻¹ while the concentrations of biochar were 1.7 to 5.6 µg·g⁻¹,
190 making the concentration in the liquid 5–140 times larger than in the char. The distribution of the PAH and
191 oxy-PAH in the liquid fraction tended to be lighter species, with less rings, compared to the char. All six-
192 ringed PAHs the liquid samples were below LOQ, N-PAC concentrations in the liquid fraction were compared
193 to the PAH and oxy-PAH concentrations too low to be included in the Fig 3, but except for wheat straw
194 pyrolyzed at 550 °C, 80 % or more of the total N-PAC were found in the liquid fraction. For the wheat straw
195 sample equal amounts were found in both liquid and char. Fagernäs et al. (2012) found that 62%, 37%, and

196 only 0.6% of the PAHs occurred in the tars, gases, and the char, respectively. We did not measure the PAH
197 concentration of the gases, but found that a considerably higher amount of PAHs occurred in the pyrolysis
198 liquids than in the solids/char (PAH content of the solids: 0.3–9.3%). This demonstrates that PAH separation
199 from char, via evaporation, is very effective. However, to prevent PAH deposition onto the biochar, contact
200 between pyrolysis vapors (liquids and gases) and char in the very cold sections of the pyrolysis unit must be
201 avoided.

202 Regardless of the operating conditions during the softwood and wheat straw runs, the PAH, oxy-PAH, and
203 N-PAC content of the biochars decreased with increasing pyrolysis temperature, whereas the PAH content
204 of the liquid fraction increased. These results suggest that although pyrolysis at 700 °C yields more PAHs
205 (than pyrolysis at 550 °C), this process can generate biochars with lower levels of these potentially toxic
206 compounds, as most PAHs evaporate from the char.

207

208 **Polychlorinated dibenzo *p*-dioxins and furans**

209 Consistent with a previous study (Wiedner et al. 2013), the results from this screening study showed that
210 extractable polychlorinated aromatics species occur at almost negligible levels in the biochar matrix. Some
211 PCDDs and PCDFs in the biochar, although detectable, were non-quantifiable ($LOQ_{PCDF}: 0.2 \text{ pg}\cdot\text{g}_{\text{biochar}}^{-1}$,
212 $LOQ_{PCDD}: 0.3 \text{ pg}\cdot\text{g}_{\text{biochar}}^{-1}$). Monochlorinated dibenzofuran (MoCDF) was the only homolog that occurred with
213 concentrations exceeding blank concentrations by some margin (defined as blank concentration times five),
214 and this occurred in only seven of the thirteen biochars. Formation of MoCDF occurred more easily (and
215 was therefore favored) at lower pyrolysis temperature and at larger pyrolysis unit (Stage II and Stage III)
216 (data not shown), than at high pyrolysis temperatures and smaller scale. However, quantification of mono-
217 to trichlorinated dioxins and furans in the liquid fraction was prevented by considerable matrix interference.
218 Similarly, highly chlorinated congeners (hepta- and octachlorinated dioxins and furans) in the liquid fraction
219 obtained from softwood and anaerobic digestate at 550 °C were non-quantifiable ($LOQ 4 \text{ pg}\cdot\text{g}_{\text{biochar}}^{-1}$).

220 As the potential concentration of toxic PCDD and PCDF congeners in the biochars could not be calculated,
221 approximate values were obtained by assigning to each congener a concentration equal to the LOQ values.
222 Using this criterion, maximum concentrations of $0.6\text{--}0.9 \text{ pg}_{\text{TEQ}}\cdot\text{g}_{\text{biochar}}^{-1}$, which are slightly higher than TEQ
223 concentrations reported for biochars generated from slowly pyrolyzed biomass (Hale et al. 2012), are
224 expected for the toxic components of the biochars. The estimated worst-case TEQ concentrations are lower
225 than the PCDD and PCDF threshold ($17 \text{ pg}_{\text{TEQ}}\cdot\text{g}_{\text{biochar}}^{-1}$) established by IBI for biochars that will be used as soil
226 amendment (International Biochar Initiative, 2015). As in the case of PAHs, regardless of the temperature,

227 configuration or size of the pyrolysis unit, the biochars are expected to have low environmental impact
228 when used for soil-improvement purposes.

229 Using LOQ concentrations yielded an estimated worst-case TEQ concentration of $\sim 1 \text{ pg}_{\text{TEQ}} \cdot \text{g}_{\text{biochar}}^{-1}$ for the
230 liquid fraction.

231 **Conclusions**

232 The influence of temperature and type/size of the pyrolysis unit on the concentration of four groups of toxic
233 contaminants was evaluated in biochars from three different biomass feedstocks representing three major
234 types of biomass, namely: forestry and agricultural residues, and organic waste. The results revealed that
235 the type of biomass has a significant influence on the concentration of PAH, oxy-PAH, and N-PAC; the
236 configuration and type/size of the pyrolysis unit have a significant effect only on wheat straw pyrolyzed at
237 550 °C.

238 This study represents the first-ever investigation where the content of oxy-PAH and N-PAC contaminants in
239 biochars is determined. The results showed that in all cases this content is considerably lower than the PAH
240 concentration. Regardless of the pyrolysis temperature, the PAH, oxy-PAH, and N-PAC concentrations were
241 much higher in the liquid fraction compared to the char fractions. The PDCCs and PCDFs occurred at
242 negligible levels in the studied biochars. Moreover, in terms of PAH, PCDD, and PCDF content, and
243 regardless of the temperature and pyrolysis unit, the biochars are expected to have low negative
244 environmental impact related to these contaminants when used for soil amendment. This demonstrates
245 that biochar with extremely low content of organic pollutants can be produced from a range of materials
246 and by using various technologies, which is an important milestone on the way to widespread biochar
247 deployment and commercialization.

248

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254

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FIGURE CAPTIONS

Fig.1 Total concentration and distribution of different-sized PAHs (numbers of rings) in each biochar. SI-SIII: size of the pyrolysis equipment (Stage I, Stage II, and Stage III, respectively) and AD: anaerobic digestate. Red dashed line represents the range of lower-limit threshold values (set by IBI (International Biochar Initiative, 2015)) for PAHs in biochar used in soil.

Fig. 2 Concentrations (plotted on different scales) of oxy-PAH (columns) and N-PAC (bullets) in biochar from the different pyrolysis units. SI-SIII: size of the pyrolysis equipment (Stage I, Stage II, and Stage III, respectively) and AD: anaerobic digestate

Fig. 3 Distribution of PAH, O-PAH, and N-PAC in char, and PAH and O-PAH in the liquid fraction. N-PAC in the liquid fraction is not shown since the corresponding concentrations were below the limit of quantification (LOQ)

Figure 1

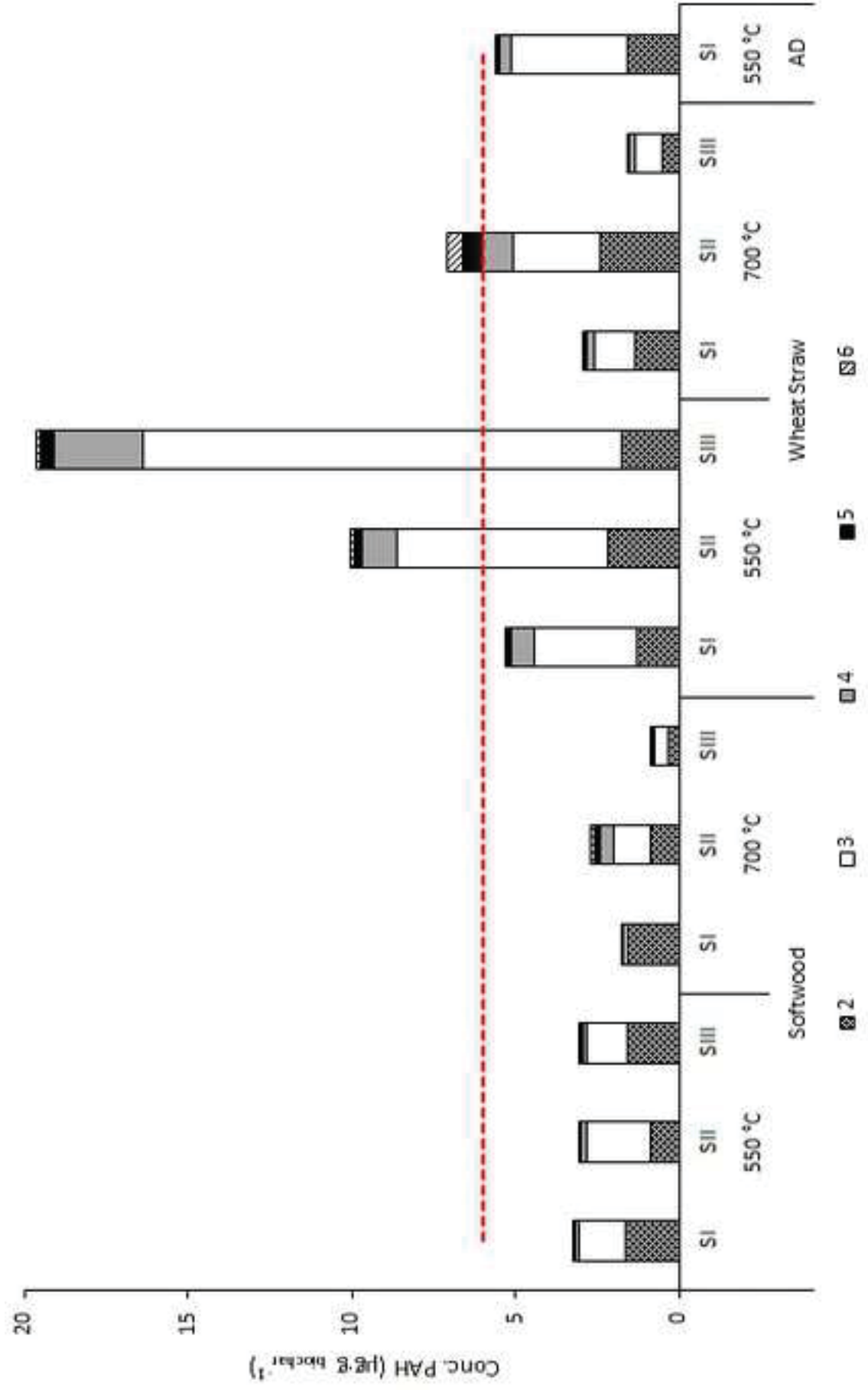
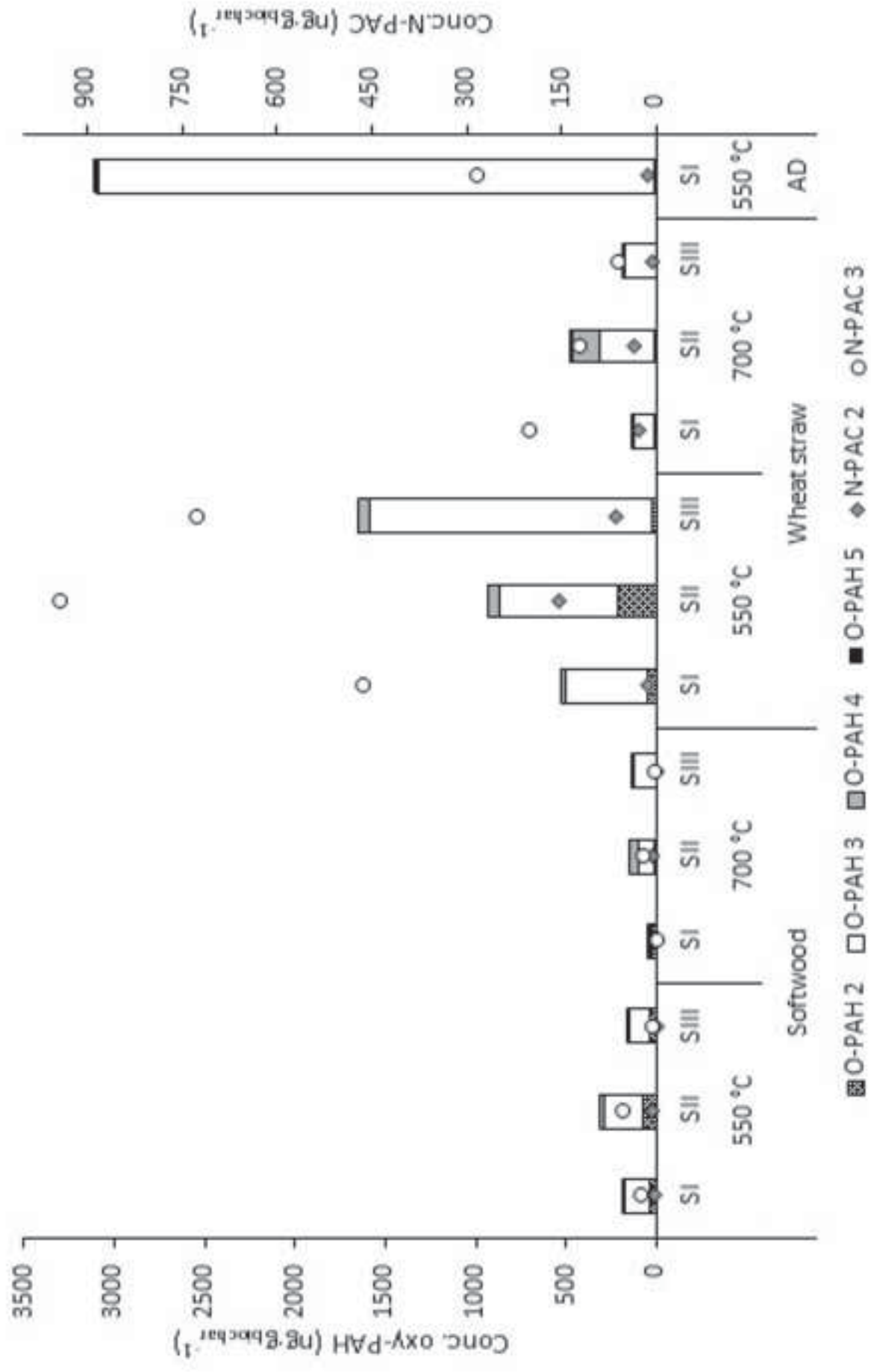


Figure 2

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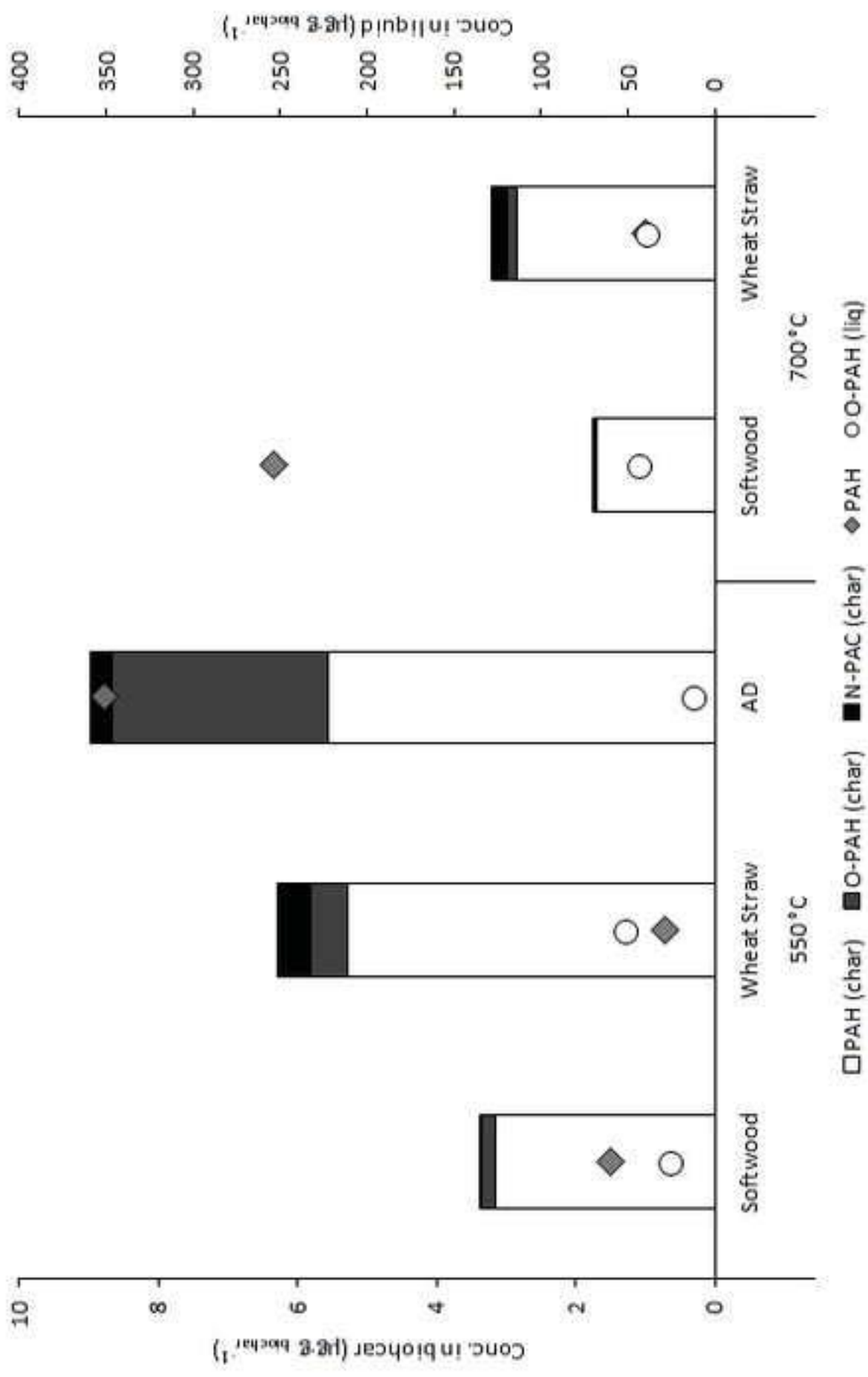


Table 1 Proximate and ultimate analysis for the studied feedstocks

	Unit	Softwood	Wheat Straw	Anaerobic Digestate
Moisture	wt ¹ .% (a.r) ²	6.71 ± 0.03 (5)	7.22 ± 0.22 (5)	5.72 ± 0.27 (6)
Volatiles	wt.% (d.b.) ³	83.6 ± 0.4 (5)	76.3 ± 0.5 (5)	64.6 ± 0.4 (6)
Fixed Carbon	wt.% (d.b.)	14.4 ± 0.4 (5)	16.6 ± 1.1 (5)	7.7 ± 0.3 (6)
Ash	wt.% (d.b.)	1.1 ± 0.1 (5)	7.0 ± 0.3 (5)	27.8 ± 0.5 (6)
C	wt.% (d.b.)	49.9 (2)	45.2 (2)	38.0 (2)
H	wt.% (d.b.)	6.6 (2)	5.4 (2)	0.60 (2)
N	wt.% (d.b.)	< 0.10 (2)	0.58 (2)	4.29 (2)

¹wt: weight; ²a.r.: as received; ³d.b.: dry basis; (n): number of replicates

Table 2 Characteristics of the pyrolysis reactors used in this study

Name	Operation mode	Temperature	Type of heating	Capacity	Carrier gas flow	Ref.
Stage I	batch	max ~ 1200 °C	infra-red furnace	30 - 50 g·run ⁻¹	0.3 L·min ⁻¹	Crombie et al., 2013
Stage II	continuous - auger	max ~ 850 °C	electric split-tube furnace	500 g·h ⁻¹	1 L·min ⁻¹	Buss et al., 2016-b
Stage III	continuous - rotary kiln	max ~ 850 °C	set of electric heaters	30 - 50 kg·h ⁻¹	10 L·min ⁻¹	Buss et al., 2014

Table 3 Overview of pyrolysis experiments. X denotes the samples that were analyzed for contaminants. In addition, the product yields for the Stage I unit are shown with the number of replicates in parentheses

Feedstock		Stage I				Stage II		Stage III	
		550 °C	Yield (%) 550 °C	700 °C	Yield (%) 700 °C	550 °C	700 °C	550 °C	700 °C
Softwood	Biochar	X	21 ± 1.1 (4)	X	19 ± 0.5 (4)	X	X	X	X
	Liquid	X	46 ± 1.1	X	45 ± 0.9				
	Gas		33 ± 2.1		36 ± 0.8				
Wheat Straw	Biochar	X	25 ± 0.5 (3)	X	23 ± 0.8 (3)	X	X	X	X
	Liquid	X	44 ± 0.3	X	44 ± 0.8				
	Gas		31 ± 0.7		33 ± 0.8				
Anaerobic Digestate	Biochar	X	25 ± 1.5 (7)						
	Liquid	X	49 ± 1.3						
	Gas		26 ± 1.2						

Table 4 List of analyzed PAH, oxy-PAH, and N-PAC and the number of aromatic rings (n_{Ar}) in each structure

PAH	n_{Ar}	Oxy-PAH	n_{Ar}	N-PAC	n_{Ar}
Naphthalene	2	1-Indanone	2	Quinoline	2
Acenaphthylene		1-Acenaphthenone		Benzo[h]quinoline	
Acenaphthene		9-Fluorenone		Acridine	3
Fluorene	3	Anthracene-9,10-dione	3	Carbazole	
Phenanthrene		2- Methylanthracene- 9,10- dione			
Anthracene		Cyclopentaphenanthrenone			
Fluoranthene		Benzo[a]fluorenone			
Pyrene		Benz[de]anthracen-7-one	4		
Benzo[a]anthracene	4	Benzo[a]anthracene-7,12-dione			
Chrysene		Naphthacene-5,12-dione			
Benzo[b]fluoranthene		Benzo[cd]pyren-6-one	5		
Benzo[k]fluoranthene					
Benzo[a]pyrene	5				
Dibenz[ah]anthracene					
Indeno[cd]pyrene					
Benzo[ghi]perylene	6				

n_{Ar} : number of aromatic rings in each structure