



HAL
open science

Linking biochar properties to biomass of basil, lettuce and pansy cultivated in growing media

Cécile Nobile, Julia Denier, David Houben

► **To cite this version:**

Cécile Nobile, Julia Denier, David Houben. Linking biochar properties to biomass of basil, lettuce and pansy cultivated in growing media. *Scientia Horticulturae*, 2020, 261, pp.109001. <10.1016/j.scienta.2019.109001>. <hal-02427204>

HAL Id: hal-02427204

<https://hal.science/hal-02427204v1>

Submitted on 3 Jan 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

1 Linking biochar properties to biomass of basil, lettuce and 2 pansy cultivated in growing media

3 Cécile Nobile ^{1,*}, Julia Denier ¹ and David Houben ^{1,*}

4 ¹ UniLaSalle, AGHYLE UP 2018.C101, 60000 Beauvais, France; cecile.nobile@unilasalle.fr (C.N.);

5 julia.denier@etu.unilasalle.fr (J.D.); david.houben@unilasalle.fr (D.H.)

6 * Correspondence: cecile.nobile@unilasalle.fr (C.N.); david.houben@unilasalle.fr (D.H.); Tel.: +33 3 44 06
7 93 45 (D.H.)

8 Abstract

9 The use of biochar as an additive for growing media for the production of potted plants requires a
10 sound knowledge of how its properties impact plant biomass production. This study aims at linking
11 physical and chemical properties of biochar with horticultural crop biomass. For this purpose, we
12 incorporated six different biochars into growing medium and grew basil (*Ocimum basilicum* L.),
13 lettuce (*Lactuca sativa* L. var. *crispa*) and pansy (*Viola wittrockiana* Gams.) for one month in
14 greenhouse conditions. We found that physical and chemical properties of biochars had a
15 significant impact on plant growth. Biochars with low density and high porosity promoted the
16 biomass of basil and lettuce. While nutrient concentration in biochars had no impact on plant
17 growth, lettuce and pansy biomasses decreased with increasing biochar pH and basil biomass
18 decreased with increasing biochar electrical conductivity. By identifying which biochar properties
19 influence plant biomass, our study allows selection of the biochars which are the best suited for
20 incorporation into growing media.

21 **Keywords:** compost; sustainability; peat; pot experiment; waste management

22

23

24

25 1. Introduction

26 Over the last decade, biochar has attracted increasing attention for addressing environmental
27 and agronomical issues. Owing to its beneficial properties, such as rich carbon (C) content, generally
28 high cation exchange capacity (CEC) and large surface area, biochar has been extensively used to
29 improve soil fertility, remediate soil and treat wastewater (Ahmad *et al.*, 2014; Biederman and
30 Harpole, 2013; Houben *et al.*, 2017; Pourret and Houben, 2018).

31 More recently, biochar has also been considered as an appropriate additive or even a substitute for
32 conventional growing media (Banitalebi *et al.*, 2019). Growing media are soilless substrates that
33 provide plants with nutrients, air and water, and physical support (Kaudal *et al.*, 2016). Important
34 properties for the use of materials for growing media include pH and electrical conductivity (EC)
35 because too high or too low pH and/or high EC can mitigate plant growth and quality (Bunt, 1988).
36 According to Abad (2001), an “ideal substrate” should have a pH ranging from 5.3 to 6.5 and EC ≤
37 0.5 dS m⁻¹. Plant growth also depends highly on physical properties of the growing medium,
38 especially porosity and density, which is related to their effects on available water content
39 (Bilderback *et al.*, 2005). Another important parameter for the production of potted plants is the
40 stability of the growing medium as it is generally desired that physical and chemical properties
41 remain stable over the crop growth period (Dalias *et al.*, 2018).

42 Growing media are commonly made from peat and aggregates (perlite and vermiculite) but the
43 negative impact on the environment and the high cost of their production warrant the use of
44 alternative products (Barrett *et al.*, 2016). For a few years, it has been suggested that addition of
45 biochar to growing media could reduce the use of these eco-unfriendly materials while improving
46 their properties such as nutrient availability, water retention, alkalinity and biological activity

47 (Lévesque *et al.*, 2018; Nemati *et al.*, 2015). However, the benefit of incorporating biochar into
48 growing media is still controversial because, although several studies reported a positive effect on
49 plant growth (Graber *et al.*, 2010; Méndez *et al.*, 2015; Tian *et al.*, 2012), others showed no or even
50 a negative effect (Steiner and Harttung, 2014; Vaughn *et al.*, 2013). These discrepancies might be
51 explained by the wide variety of biochars used by researchers. Feedstock and pyrolysis conditions
52 drive biochar properties, which can in turn mediate their effects on plant growth (Li *et al.*, 2019).

53 In order to select and design biochars which are the best suited for incorporation into growing
54 media, it is essential to identify which physical and chemical properties of the biochars play the
55 major roles on plant growth. The objective of the present study was therefore: (i) to determine the
56 response of horticultural crop biomass grown in growing media to the presence of contrasted
57 biochars and (ii) to identify the physical and chemical properties of the biochars responsible for their
58 effects on plant biomass.

59 **2. Materials and Methods**

60 *2.1. Biochars*

61

62 Commercial grade biochars were obtained from VTGreen (Allier, France) using an industrial
63 pyrolysis reactor (Biogreen® Technology, ETIA, Oise, France). The principle employing continuous
64 thermal treatment without oxygen with a set residence time of 10 min. Feedstocks available in large
65 quantities in France, ensuring a high supply and having a low initial value, were selected for biochar
66 production: coffee residues, resulting from coffee liqueur extraction and provided by Compomar
67 (Essone, France); wood granules (<8 mm) from resinous trees provided by a wood storage center
68 (LCE, Maine-et-Loire, France); maize cobs cultivated, dried and crushed by Agrivalor (Alsace, France);
69 rapeseed straws cultivated, dried and crushed by Agriopale (Pas-de-Calais, France); and green
70 wastes compost rejects composed of poplar and conifers branches and provided by Fertilvert (Seine-

71 Maritime, France). The temperature of pyrolysis was 550°C for wood granules (hereafter referred
72 as Wood BC), 450°C for maize cobs and green compost rejects (hereafter referred as Maize BC and
73 Compost BC, respectively), 650°C for rapeseed straws (hereafter referred as Rapeseed BC) and
74 450°C and 650°C for coffee residues (hereafter referred as Coffee450 BC and Coffee650 BC,
75 respectively). The different pyrolysis temperatures were selected to obtain biochars with
76 contrasting chemical and physical properties.

77 Biochars were analyzed for pH (AFNOR, 2012a), EC (AFNOR, 2012b), CEC (AFNOR, 1999),
78 density, porosity (AFNOR, 2012c), organic C content (AFNOR, 2011), total nitrogen (N) content
79 (AFNOR, 2002a)), C:N ratio, ash content at 815°C (ISO, 2016), phosphorus (P), potassium (K), calcium
80 (Ca) and magnesium (Mg) contents (AFNOR, 2002b).

81

82 *2.2. Growing medium-biochar mixtures*

83 Each biochar was incorporated at 10 % (v/v) into a growing medium made of 60% of sphagnum
84 blond peat (Gamm Vert, France), 15% of green waste compost (Fertivert, Seine-Maritime, France),
85 10% of composted manure and grape pomace (BioFumur®, Terre et Nature, France), and 5% of 0-4
86 mm build sand (Cantillana, Gamm Vert, France).

87

88 *2.3. Greenhouse pot experiment*

89 Horticultural plants largely cultivated in growing media and belonging to different families, thus
90 having potential different responses to biochar addition were tested: basil, lettuce, and pansy. Basil,
91 lettuce and pansy seeds were individually sown in 80 mL pots filled with commercial seed substrate
92 (Gamm Vert, France), kept under controlled greenhouse conditions (temperature 24/16°C;
93 day/night, 16 h photoperiod) and watered by adding demineralized water two times a week. Three-
94 week old seedlings of basil and lettuce, and four-week old seedlings of pansy were then transplanted
95 separately in the six biochar-enriched media. Basil seedlings were transplanted in 0.5 L pots
96 containing 80 g dry weight (DW) equivalent of medium, while lettuce and pansy were transplanted

97 in 1.6 L pots containing 180 g DW equivalent of medium. The trials were conducted under the same
98 controlled greenhouse conditions in four replicates. Throughout the experiment, the moisture
99 content of each growing medium was kept at 80% water holding capacity (WHC) by adding
100 demineralized water and weighing the pots four times a week. After one month, aboveground parts
101 of plants were harvested, dried at 60°C for 48 h and weighed.

102

103 *2.4. Statistical analyses*

104 Data analysis was performed using Rstudio (Version 0.99.903). Correlations between physical
105 and chemical biochar properties and biomass of basil, lettuce or pansy were analyzed using the
106 Pearson correlation coefficient. The significance of the medium effect on basil, lettuce and pansy
107 biomass was tested by one-way ANOVA and Tukey's HSD test was used to identify the differences
108 between media. All tests of significance were conducted at $P < 0.05$.

109

110 **3. Results**

111 *3.1. Biochar properties*

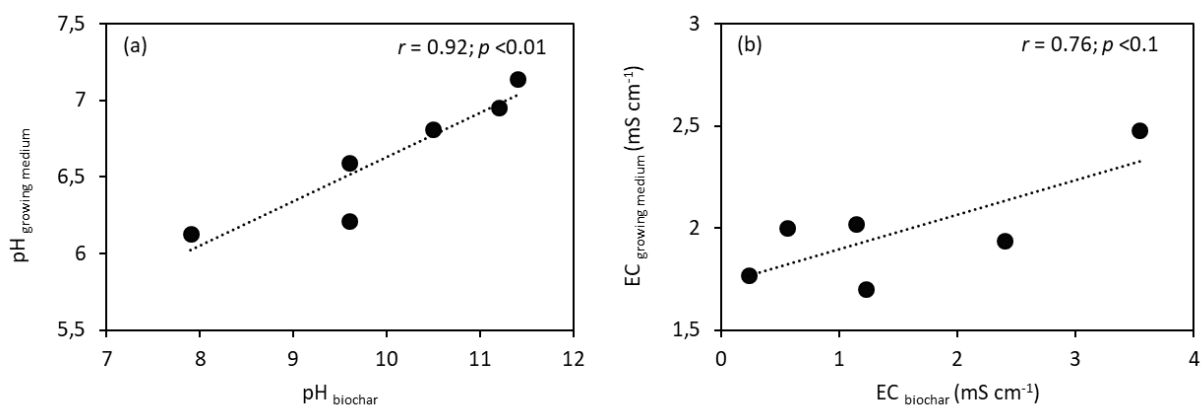
112 The six biochars tested in this study showed contrasting physical and chemical properties (Table
113 1). Although all the biochars were alkaline, their pH ranged from 7.90 (Wood BC) to 11.40 (Compost
114 BC). The pH of growing media after biochar application was positively correlated to biochar pH (Fig.
115 1a). The EC was the lowest for the two coffee-derived biochars and the highest for Compost BC. A
116 weak positive correlation between growing media EC and biochar EC was found (Fig. 1b). This
117 relationship was, however, mainly driven by the biochar, with the highest biochar EC value (Compost
118 BC) increasing markedly the growing medium EC. The CEC differed greatly among the biochars,
119 ranging from 2.90 $\text{cmol}_c \text{ kg}^{-1}$ (Rapeseed BC) to 32.4 $\text{cmol}_c \text{ kg}^{-1}$ (Coffee650 BC). Rapeseed BC had the
120 highest porosity and the lowest density, while Wood BC and Compost BC had the lowest porosity
121 and the highest density. Organic carbon (C) content was high for all the biochars, ranging from

122 31.55% (Compost BC) to 48.75% (Wood BC). Total nitrogen (N) content was lower than 1%, except
 123 for the two coffee biochars with 4.21% (Coffee450 BC) and 3.92% (Coffee650 BC). Consequently the
 124 C:N ratio was the lowest for the coffee biochars and the highest for Wood BC. Biochars showed also
 125 very different concentrations in nutrients. Irrespective of the nutrient, Wood BC and Rapeseed BC
 126 had low and high nutrient concentrations, respectively. The highest concentration of K was recorded
 127 for Coffee650 BC and Compost BC exhibited the higher concentration of Mg.

128 **Table 1.** Biochar properties

		Wood BC	Rapeseed BC	Maize BC	Compost BC	Coffee450 BC	Coffee650 BC
pH		7.90	11.20	9.60	11.40	9.60	10.50
EC	dS m ⁻¹	2.40	1.22	1.14	3.54	0.23	0.56
CEC	cmol _c kg ⁻¹	12.30	2.90	27.30	8.50	15.20	32.40
Porosity	%	87.30	95.90	88.50	86.30	93.00	92.60
Density	g L ⁻¹	281.00	73.00	171.00	291.00	110.00	108.00
Organic C	%	48.75	35.30	45.35	31.55	42.65	46.00
Total N	%	0.18	0.81	0.68	0.84	4.21	3.92
C:N		270.83	43.58	66.69	37.56	10.13	11.73
Ash 815°C	%	2.10	16.80	7.00	26.30	4.20	6.20
P	mg kg ⁻¹	611	3753	1353	3709	2662	2357
K	mg kg ⁻¹	2739	18179	16519	17847	11538	18926
Ca	mg kg ⁻¹	1787	66172	2358	34015	2001	1072
Mg	mg kg ⁻¹	482	4161	1025	5066	2171	1267

129



130

131 **Figure 1.** Relationships between biochar pH and growing medium pH (a) and biochar electrical conductivity
 132 (EC) and growing medium EC (b).

133

134 3.2. Basil

135 The nature of biochar incorporated into the medium significantly impacted the biomass of basil (Fig.
136 2a). Basil grown in media containing Coffee450 BC (2.2 ± 0.16 g) or Rapeseed BC (2.1 ± 0.12 g) had
137 significantly greater biomass than those grown in media containing other biochars. The four other
138 biochars induced similar basil biomasses, with a minimum obtained with the compost BC (1.0 ± 0.24
139 g). Correlations between basil biomass and biochars physical and chemical properties showed that
140 biomass was significantly and positively correlated with the porosity of the biochars ($r = 0.65$), and
141 significantly and negatively correlated with the EC ($r = -0.45$), the CEC ($r = -0.44$) and the bulk density
142 ($r = -0.54$) of the biochars (Table 2).

143

144 3.3. Lettuce

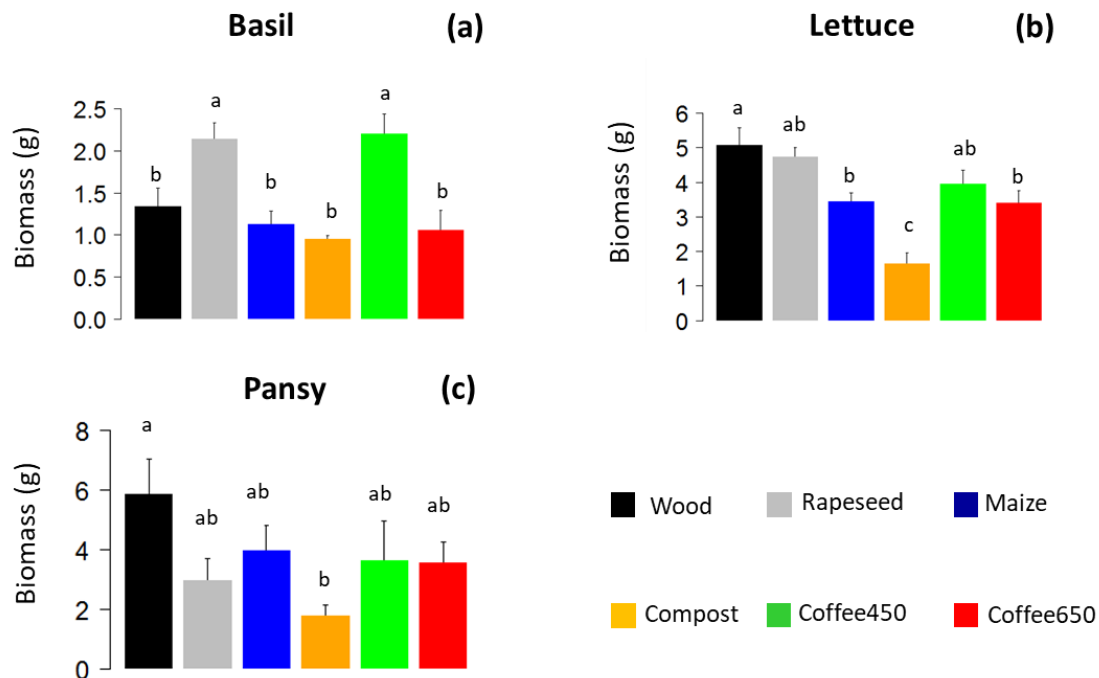
145 Biochars leading to the highest lettuce biomasses were Wood BC (5.1 ± 0.51 g), Rapeseed BC
146 (4.8 ± 0.48 g), and Coffee450 BC (4.0 ± 0.38 g) (Fig. 2b). The lowest lettuce biomass was obtained
147 with Compost BC (1.7 ± 0.24 g), and was significantly lower than with all other biochars. Biomass
148 was significantly and positively correlated with the porosity ($r = 0.49$) of the biochars and
149 significantly and negatively correlated with the pH ($r = -0.44$) and the ash content ($r = -0.51$) (Table
150 2).

151

152 3.4. Pansy

153 The highest pansy biomass was obtained with Wood BC (5.9 ± 1.16 g), but was significantly
154 higher than the biomass obtained with Compost BC (1.8 ± 0.36 g) only (Fig. 2c). Biomass was
155 significantly and positively correlated with the organic C ($r = 0.55$) content and the C:N ratio ($r = 0.5$)

156 of the biochars, and significantly and negatively correlated with pH ($r = -0.59$), P content ($r = -0.57$),
 157 and ash content ($r = -0.53$) (Table 2).
 158



159 **Figure 2.** Average biomass of basil (a), lettuce (b) and pansy (c) in the presence of biochar. Data are
 160 presented as mean \pm standard deviation. Columns with same letter do not differ significantly at the 5% level
 161 according to the Tukey's multiple comparison test.
 162
 163

164 **Table 2.** Pearson's correlation coefficients between basil, lettuce and pansy biomass and physical
 165 and chemical properties of biochars. Correlation coefficients are significant at $p < 0.05$; ns means
 166 non-significant.

	Basil	Lettuce	Pansy
pH	ns	-0.44	-0.59
EC	-0.45	ns	ns
CEC	-0.44	ns	ns
Porosity	0.65	0.49	ns
Density	-0.54	ns	ns
Organic C	ns	ns	0.55
Total N	ns	ns	ns
C:N	ns	ns	0.5
Ash 815°C	ns	-0.51	-0.53
P	ns	ns	-0.57
K	ns	ns	ns
Ca	ns	ns	ns

Mg ns ns ns

167
168
169

170 **4. Discussion**

171 The six biochars used in this study comprised a wide array of physical and chemical properties.
172 Overall, properties of the present biochars compared well with the values reported by other
173 researchers for similar feedstock materials and pyrolysis conditions (Houben *et al.*, 2014; Sun *et al.*,
174 2014; Zhao *et al.*, 2013) and followed similar trends, e.g. ash content of wood-derived biochars was
175 lower than that of non-wood-derived biochars (Mukome *et al.*, 2013). Our data highlight the role of
176 pyrolysis temperature on biochar properties since, for instance, Coffee biochar produced at 650°C
177 had a higher pH than Coffee biochar produced at 450°C, which is consistent with the literature and
178 can be explained by the concomitant increase in ash content (Table 1) and decrease in acidic
179 functional groups (Enders *et al.*, 2012). Similarly to pH, EC of biochars was affected by pyrolysis
180 temperature (EC of Coffee650 BC is 2.4 times higher than EC of Coffee450 BC), which was due to the
181 release of soluble salts from organic compounds during pyrolysis (Banitalebi *et al.*, 2019). However,
182 our data also evidenced the role played by feedstock materials since, for instance, Wood BC had a
183 much lower pH than Maize BC, Compost BC and Coffee450 BC. Like pH, feedstock materials played
184 also a significant role on biochar EC since, for instance, biochars produced at the same temperature
185 displayed a wide range of EC. Consistently with the literature (Li *et al.*, 2019), final properties of
186 biochar resulted thus from the combined effect of their different feedstock materials and pyrolysis
187 conditions.

188

189 As expected, the incorporation of the six dissimilar biochars into growing media yielded
190 dissimilar plant biomass responses. Increasing porosity usually improves water and air exchanges in
191 the growing media. As shown by Liu *et al.* (2017), the impact of biochar on soil water retention is
192 strongly dependent on its porosity. Consistently with Roehrdanz *et al.* (2019), our results indicated

193 that incorporating biochar with low density and high porosity led to higher biomass production for
194 basil and lettuce, respectively, which is most likely related to their beneficial effects on water
195 availability. This is in line with Méndez *et al.* (2015) showing that biomasses of lettuce grown on pea-
196 based growing media amended with biochar were positively related to the improvement of
197 hydrophysical growing media properties.

198

199 In the present study, lettuce and pansy biomasses were significantly negatively correlated with
200 biochar pH, which reflects the high sensitivity of these crops to elevated pH, as already reported by
201 previous studies (Kuehny and Morales, 1998; Logan and Lindsay, 1996; Roosta, 2011). By increasing
202 pH of growing media, alkaline amendments such as biochar can decrease nutrient availability,
203 mainly for P, Fe and Mn, resulting in lower yield (Belda *et al.*, 2013). It must be noted that the
204 negative correlations between lettuce and pansy biomasses and ash content most likely result from
205 the strong relationship between ash content and basicity of biochars (Mukome *et al.*, 2013).

206

207 High EC reflects high levels of soluble salts that, through decreasing osmotic potential, may limit
208 the availability of water to plants, thereby limiting germination and plant growth (Nieto *et al.*, 2016).
209 Previous studies have evidenced that biochar might impair the growth of plants due to osmotic
210 stress induced by high biochar EC (Rajkovich *et al.*, 2012; Revell *et al.*, 2012). In the present study,
211 the significant negative correlation between basil biomass and biochar EC suggests that the growth
212 of this crop was negatively impacted by the incorporation of biochar with high EC. These results are
213 in line with other researchers reporting a decreasing basil biomass, as well as lower transpiration
214 and chlorophyll content, with increasing levels of salinity (Bekhradi *et al.*, 2015). Oppositely, the lack
215 of significant correlation between EC and biomass of lettuce and pansy might indicate a lower EC
216 sensitivity, as shown for instance by van Iersel (1999) for pansy.

217

218 Since addition of biochar with high organic C content and elevated C:N ratio usually improves
219 substrate stability because it decreases its decomposition, the positive correlation between pansy
220 biomass and these two biochar properties might be due to a higher growing media stability, a
221 parameter which was previously found to strongly affect the growth of pansy (Burnett *et al.*, 2016;
222 Purman and Gouin, 1992). However, this should be further investigated by, among others,
223 characterizing the changes of properties of growing media over time.

224

225 Finally, except for the unexpected negative correlation between pansy biomass and P
226 concentration in biochar, crop biomasses were not correlated with nutrient concentrations of
227 biochar. This suggests that the effects of biochar incorporation into growing media on plant growth
228 do not primarily rely on their nutrient composition but rather on other properties, including their
229 pH, EC, porosity and density. It must, however, be noted that the present study only focused on the
230 relationship between biochar properties and plant biomass. Further study on other physiological
231 traits should be carried out because they could be more sensitive to changes in biochar properties
232 than plant biomass. For instance, since pansy flowering is dependent on nutrient availability in the
233 substrate (Zawadzińska and Janicka, 2007), it is important to determine whether nutrient
234 concentration in biochar impacts flowering abundance and time. In addition, since the aim of this
235 study was to examine how the biochar properties mediated the plant response, we did not consider
236 the influence of the initial properties of the growing medium in which we incorporated each of the
237 six biochars. Because biochar properties may be themselves mediated by the surrounding
238 environment, e.g. soil properties (Hardy *et al.*, 2016), biological activity (Houben and Sonnet, 2015;
239 Lehmann *et al.*, 2011), the next challenge will be to elucidate how the composition of the growing
240 medium drives the plant response to biochar application. In a more general context, it will be
241 essential that, besides having the properties suitable for plant production as identified in this study
242 and others (Nemati *et al.*, 2015; Singh *et al.*, 2010), biochars selected for plant production meet
243 quality standards (Meyer *et al.*, 2017).

244

245 **5. Conclusions**

246 Our results have confirmed that the efficacy of biochar incorporation into growing media to
247 improve plant biomass is not only dependent on the properties of the biochar itself but also on the
248 crop species. However, general patterns can be drawn. First, increasing biochar pH and EC had
249 generally a detrimental effect on plant biomass while biochars with low density and/or high porosity
250 were beneficial for plant growth. Second, irrespective of the plant species, nutrient concentrations
251 were not related to plant biomass. By linking physical and chemical properties of biochar with plant
252 biomass, this study provides insights to engineer and better select biochar for incorporation into
253 growing media for potted plants production.

254

255

256 **Acknowledgments:** This research was funded by Bpifrance and the Région Hauts-de-France (FUI
257 Biochar 2021). All the members of the “FUI Biochar 2021” project are gratefully acknowledged for
258 their useful comments on this paper. We thank ETIA, VTGreen and Agriculteurs Composteurs de
259 France for providing biochars and growing media.

260 **References**

- 261 Abad, M., Noguera, P., Burés, S., 2001. National inventory of organic wastes for use as growing media for
262 ornamental potted plant production: case study in Spain. *Bioresource Technology* 77, 197–200.
263 [https://doi.org/10.1016/S0960-8524\(00\)00152-8](https://doi.org/10.1016/S0960-8524(00)00152-8)
- 264 AFNOR, 2012a. NF EN 13037. Soil improvers and growing media - Determination of pH. AFNOR, Paris.
- 265 AFNOR, 2012b. NF EN 13038. Soil improvers and growing media - Determination of electrical conductivity.
266 AFNOR, Paris.
- 267 AFNOR, 2012c. NF EN 13041. Soil improvers and growing media - Determination of physical properties - Dry
268 bulk density, air volume, water volume, shrinkage value and total pore space. AFNOR, Paris.
- 269 AFNOR, 2011. NF EN 13039. Soil improvers and growing media - Determination of organic matter content
270 and ash. AFNOR, Paris.
- 271 AFNOR, 2002a. NF EN 13654-1. Soil improvers and growing media - Determination of nitrogen - Part 1 :
272 modified Kjeldahl method. AFNOR, Paris.
- 273 AFNOR, 2002b. NF EN 13650. Soil improvers and growing media - Extraction of aqua regia soluble elements.
274 AFNOR, Paris.
- 275 AFNOR, 1999. NF X31-130. Soil quality - Chemical methods - Determination of cationic exchange capacity (CEC)
276 and extractible cations. AFNOR, Paris.
- 277 Ahmad, M., Rajapaksha, A.U., Lim, J.E., Zhang, M., Bolan, N., Mohan, D., Vithanage, M., Lee, S.S., Ok, Y.S.,
278 2014. Biochar as a sorbent for contaminant management in soil and water: A review. *Chemosphere*
279 99, 19–33. <https://doi.org/10.1016/j.chemosphere.2013.10.071>
- 280 Banitalebi, G., Mosaddeghi, M.R., Shariatmadari, H., 2019. Feasibility of agricultural residues and their
281 biochars for plant growing media: Physical and hydraulic properties. *Waste Management* 87, 577–
282 589. <https://doi.org/10.1016/j.wasman.2019.02.034>
- 283 Barrett, G.E., Alexander, P.D., Robinson, J.S., Bragg, N.C., 2016. Achieving environmentally sustainable growing
284 media for soilless plant cultivation systems – A review. *Scientia Horticulturae* 212, 220–234.
285 <https://doi.org/10.1016/j.scienta.2016.09.030>
- 286 Bekhradi, F., Delshad, M., Marín, A., Luna, M.C., Garrido, Y., Kashi, A., Babalar, M., Gil, M.I., 2015. Effects of
287 salt stress on physiological and postharvest quality characteristics of different Iranian genotypes of
288 basil. *Hortic. Environ. Biotechnol.* 56, 777–785. <https://doi.org/10.1007/s13580-015-1095-9>
- 289 Belda, R.M., Mendoza-Hernández, D., Fornes, F., 2013. Nutrient-rich compost versus nutrient-poor
290 vermicompost as growth media for ornamental-plant production. *Journal of Plant Nutrition and Soil*
291 *Science* 176, 827–835. <https://doi.org/10.1002/jpln.201200325>

292 Biederman, L.A., Harpole, W.S., 2013. Biochar and its effects on plant productivity and nutrient cycling: a meta-
293 analysis. *GCB Bioenergy* 5, 202–214. <https://doi.org/10.1111/gcbb.12037>

294 Bilderback, T.E., Warren, S.L., Owen, J.S., Albano, J.P., 2005. Healthy substrates need physicals too!
295 *HortTechnology* 15, 747–751. <https://doi.org/10.21273/HORTTECH.15.4.0747>

296 Bunt, B.R., 1988. *Media and Mixes for Container-Grown Plants: A manual on the preparation and use of*
297 *growing media for pot plants*. Springer Science & Business Media.

298 Burnett, S.E., Mattson, N.S., Williams, K.A., 2016. Substrates and fertilizers for organic container production
299 of herbs, vegetables, and herbaceous ornamental plants grown in greenhouses in the United States.
300 *Scientia Horticulturae*, Recent advances in organic horticulture technology and management - Part 1
301 208, 111–119. <https://doi.org/10.1016/j.scienta.2016.01.001>

302 Dalias, P., Prasad, M., Mumme, J., Kern, J., Stylianou, M., Christou, A., 2018. Low-cost post-treatments improve
303 the efficacy of hydrochar as peat replacement in growing media. *Journal of Environmental Chemical*
304 *Engineering* 6, 6647–6652. <https://doi.org/10.1016/j.jece.2018.10.042>

305 Enders, A., Hanley, K., Whitman, T., Joseph, S., Lehmann, J., 2012. Characterization of biochars to evaluate
306 recalcitrance and agronomic performance. *Bioresource Technology* 114, 644–653.
307 <https://doi.org/10.1016/j.biortech.2012.03.022>

308 Graber, E.R., Meller Harel, Y., Kolton, M., Cytryn, E., Silber, A., Rav David, D., Tsechansky, L., Borenshtein, M.,
309 Elad, Y., 2010. Biochar impact on development and productivity of pepper and tomato grown in
310 fertigated soilless media. *Plant Soil* 337, 481–496. <https://doi.org/10.1007/s11104-010-0544-6>

311 Hardy, B., Cornelis, J.-T., Houben, D., Lambert, R., Dufey, J.E., 2016. The effect of pre-industrial charcoal kilns
312 on chemical properties of forest soil of Wallonia, Belgium. *Eur J Soil Sci* 67, 206–216.
313 <https://doi.org/10.1111/ejss.12324>

314 Houben, D., Hardy, B., Faucon, M.-P., Cornelis, J.-T., 2017. Effect of biochar on phosphorus bioavailability in
315 an acidic silt loam soil. *Biotechnol. Agron. Soc. Environ.* 21, 209–217.

316 Houben, D., Sonnet, P., 2015. Impact of biochar and root-induced changes on metal dynamics in the
317 rhizosphere of *Agrostis capillaris* and *Lupinus albus*. *Chemosphere* 139, 644–651.
318 <https://doi.org/10.1016/j.chemosphere.2014.12.036>

319 Houben, D., Sonnet, P., Cornelis, J.-T., 2014. Biochar from Miscanthus: a potential silicon fertilizer. *Plant Soil*
320 374, 871–882. <https://doi.org/10.1007/s11104-013-1885-8>

321 ISO, 2016. ISO 1171:2010. Solid mineral fuels -- Determination of ash. ISO, Geneva.

322 Kaudal, B.B., Chen, D., Madhavan, D.B., Downie, A., Weatherley, A., 2016. An examination of physical and
323 chemical properties of urban biochar for use as growing media substrate. *Biomass and Bioenergy* 84,
324 49–58. <https://doi.org/10.1016/j.biombioe.2015.11.012>

325 Kuehny, J.S., Morales, B., 1998. Effects of salinity and alkalinity on pansy and impatiens in three different
326 growing media. *Journal of Plant Nutrition* 21, 1011–1023.
327 <https://doi.org/10.1080/01904169809365460>

328 Lehmann, J., Rillig, M.C., Thies, J., Masiello, C.A., Hockaday, W.C., Crowley, D., 2011. Biochar effects on soil
329 biota – A review. *Soil Biology and Biochemistry* 43, 1812–1836.
330 <https://doi.org/10.1016/j.soilbio.2011.04.022>

331 Lévesque, V., Rochette, P., Ziadi, N., Dorais, M., Antoun, H., 2018. Mitigation of CO₂, CH₄ and N₂O from a
332 fertigated horticultural growing medium amended with biochars and a compost. *Applied Soil Ecology*
333 126, 129–139. <https://doi.org/10.1016/j.apsoil.2018.02.021>

334 Li, S., Harris, S., Anandhi, A., Chen, G., 2019. Predicting biochar properties and functions based on feedstock
335 and pyrolysis temperature: A review and data syntheses. *Journal of Cleaner Production* 215, 890–
336 902. <https://doi.org/10.1016/j.jclepro.2019.01.106>

337 Liu, Z., Dugan, B., Masiello, C.A., Gonnermann, H.M., 2017. Biochar particle size, shape, and porosity act
338 together to influence soil water properties. *PLOS ONE* 12, e0179079.
339 <https://doi.org/10.1371/journal.pone.0179079>

340 Logan, T.J., Lindsay, B.J., 1996. Growth of tree bedding plant species in soilless mixes with alkaline stabilized
341 sewage sludge. *Journal of Environmental Horticulture* 14, 160–162. [https://doi.org/10.24266/0738-
342 2898-14.3.160](https://doi.org/10.24266/0738-2898-14.3.160)

343 Méndez, A., Paz-Ferreiro, J., Gil, E., Gascó, G., 2015. The effect of paper sludge and biochar addition on brown
344 peat and coir based growing media properties. *Scientia Horticulturae* 193, 225–230.
345 <https://doi.org/10.1016/j.scienta.2015.07.032>

346 Meyer, S., Genesio, L., Vogel, I., Schmidt, H.-P., Soja, G., Someus, E., Shackley, S., Verheijen, F.G.A., Glaser, B.,
347 2017. Biochar standardization and legislation harmonization. *Journal of Environmental Engineering
348 and Landscape Management* 25, 175–191. <https://doi.org/10.3846/16486897.2016.1254640>

349 Mukome, F.N.D., Zhang, X., Silva, L.C.R., Six, J., Parikh, S.J., 2013. Use of Chemical and Physical Characteristics
350 To Investigate Trends in Biochar Feedstocks. *J. Agric. Food Chem.* 61, 2196–2204.
351 <https://doi.org/10.1021/jf3049142>

352 Nemati, M.R., Simard, F., Fortin, J.-P., Beaudoin, J., 2015. Potential use of biochar in growing media. *Vadose
353 Zone Journal* 14. <https://doi.org/10.2136/vzj2014.06.0074>

354 Nieto, A., Gascó, G., Paz-Ferreiro, J., Fernández, J.M., Plaza, C., Méndez, A., 2016. The effect of pruning waste
355 and biochar addition on brown peat based growing media properties. *Scientia Horticulturae* 199,
356 142–148. <https://doi.org/10.1016/j.scienta.2015.12.012>

357 Pourret, O., Houben, D., 2018. Characterization of metal binding sites onto biochar using rare earth elements
358 as a fingerprint. *Heliyon* 4, e00543. <https://doi.org/10.1016/j.heliyon.2018.e00543>

359 Purman, J.R., Gouin, F.R., 1992. Influence of compost aging and fertilizer regimes on the growth of bedding
360 plants, transplants and poinsettia. *Journal of Environmental Horticulture* 10, 52–54.
361 <https://doi.org/10.24266/0738-2898-10.1.52>

362 Rajkovich, S., Enders, A., Hanley, K., Hyland, C., Zimmerman, A.R., Lehmann, J., 2012. Corn growth and nitrogen
363 nutrition after additions of biochars with varying properties to a temperate soil. *Biology and Fertility
364 of Soils* 48, 271–284. <https://doi.org/10.1007/s00374-011-0624-7>

365 Revell, K.T., Maguire, R.O., Agblevor, F.A., 2012. Influence of poultry litter biochar on soil properties and plant
366 growth. *Soil Science* 177, 402. <https://doi.org/10.1097/SS.0b013e3182564202>

367 Roehrdanz, M., Greve, T., de Jager, M., Buchwald, R., Wark, M., 2019. Co-composted hydrochar substrates as
368 growing media for horticultural crops. *Scientia Horticulturae* 252, 96–103.
369 <https://doi.org/10.1016/j.scienta.2019.03.055>

370 Roosta, H.R., 2011. Interaction between water alkalinity and nutrient solution pH on the vegetative growth,
371 chlorophyll fluorescence and leaf magnesium, iron, manganese, and zinc concentrations in lettuce.
372 *Journal of Plant Nutrition* 34, 717–731. <https://doi.org/10.1080/01904167.2011.540687>

373 Singh, B., Singh, B.P., Cowie, A.L., 2010. Characterisation and evaluation of biochars for their application as a
374 soil amendment. *Soil Res.* 48, 516–525. <https://doi.org/10.1071/SR10058>

375 Steiner, C., Harttung, T., 2014. Biochar as a growing media additive and peat substitute. *Solid Earth* 5, 995–
376 999. <https://doi.org/10.5194/se-5-995-2014>

377 Sun, Y., Gao, B., Yao, Y., Fang, J., Zhang, M., Zhou, Y., Chen, H., Yang, L., 2014. Effects of feedstock type,
378 production method, and pyrolysis temperature on biochar and hydrochar properties. *Chemical*
379 *Engineering Journal* 240, 574–578. <https://doi.org/10.1016/j.cej.2013.10.081>
380 Tian, Y., Sun, X., Li, S., Wang, H., Wang, L., Cao, J., Zhang, L., 2012. Biochar made from green waste as peat
381 substitute in growth media for *Calathea rotundifolia* cv. *Fasciata*. *Scientia Horticulturae* 143, 15–18.
382 <https://doi.org/10.1016/j.scienta.2012.05.018>
383 van Iersel, M., 1999. Fertilizer concentration affects growth and nutrient composition of subirrigated pansies.
384 *HortScience* 34, 660–663. <https://doi.org/10.21273/HORTSCI.34.4.660>
385 Vaughn, S.F., Kenar, J.A., Thompson, A.R., Peterson, S.C., 2013. Comparison of biochars derived from wood
386 pellets and pelletized wheat straw as replacements for peat in potting substrates. *Industrial Crops*
387 *and Products* 51, 437–443. <https://doi.org/10.1016/j.indcrop.2013.10.010>
388 Zawadzińska, A., Janicka, D., 2007. Effects of compost media on growth and flowering of parviflorous garden
389 pansy (*Viola x wittrockiana* Gams.). Part II. Plant flowering and decorative value. *Acta Agrobotanica*
390 60, 167–171. <https://doi.org/10.5586/aa.2007.046>
391 Zhao, L., Cao, X., Mašek, O., Zimmerman, A., 2013. Heterogeneity of biochar properties as a function of
392 feedstock sources and production temperatures. *Journal of Hazardous Materials* 256–257, 1–9.
393 <https://doi.org/10.1016/j.jhazmat.2013.04.015>
394