1   **Spanish biofuels heating value estimation based on structural analysis**

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10   **Abstract**

11   The importance of waste biomass as an energy source is likely to increase

12   during the coming years as a result of European energy policy objectives, and

13   because of the wide range of possibilities that it offers: it is a cheap fuel,

14   widespread, and available in large quantities. In addition to crops and forestry

15   operations, the Spanish fruit, olive and wine industries generate large amounts

16   of currently undervalued solid wastes such as stones, branches, pulps or

17   pomaces. The use of these by-products offers environmental benefits like

18   removing waste and preventing fires at the same time as providing an energy

19   yield. A proper energy valorization will require a complete physicochemical

20   characterization. In this article, a structural and thermal characterization is

21   developed from twenty samples from the olive and wine industries, as well as

22   from forest and agro wastes. In addition, predictive equations are proposed to

23   determine higher heating value (HHV) from chemical composition. For this

24 purpose, the chemical extraction method (also called the 'classic' method) was

25 used, and results were obtained in accordance with the data shown in the

26 bibliography. Two predictive equations were developed: one based on lignin

27 and hemicellulose content, and the other based on lignin quantity. Both present

28 an absolute average error (AAE) of 0.87% and 1.13%, respectively.

29 **Keywords:** Biomass**,** high heating value**,** structural analysis**,** chemical

30 composition

31

32 1. Introduction

33 During recent years, waste biomass has gained in importance as an energy

34 feedstock due to requirements for developing various renewable energy

35 sources to reach European goals for the years 2020 (the "three 20s" target) and

36 2050.

37 Among complementary energy resources, biomass offers great possibilities,

38 including those involving direct (combustion) procedures and indirect (extractive

39 or transformative) procedures of reuse, recovery and revaluation (Barbanti et

40 al., 2014). Since biomass as waste is cheap and available nearly everywhere

41 (Masnadi et al., 2014), and is also responsible for lower emissions of

42 environmentally detrimental gases like sulphur dioxide (SO_2) and nitrogen

43 oxides (NO_x), the combustion of biomass also plays a positive role in reducing

44 global acid rain formation (Zhang et al., 2010). In addition, biomass contributes

45 approximately 14% of worldwide energy consumption (Demirbas and Demirbas,

46 2007), meaning 63% of all renewable energy sources (García-Maraver et al.,

47 2012). The work of (Krzyżaniak et al., 2014 and 2015 *in press*; Salaheldeen et

48 al., 2014), are worthy of mention as recent contributions. Woody crops

49 management, like orchards, olive groves or vineyards, generate huge amounts

50 of waste (Godin et al., 2013).

51 To achieve an efficient reuse of residual vegetable biomass, the availability of

52 the raw matter (quality, quantity, location of origin) must be reconciled with the

53 characteristics of the chosen or available technical alternatives (fundamentals of

54 procedures, optimal design capacity and location of the consumers of

55 commercial energy). The technical and economic success of most of the

56 options is thus strongly associated with geography, climate and customer

57 requirements.

58 In Spain, the biggest potential biomass source belongs to Andalucía and

59 Castilla-La Mancha, which together provide nearly 50% of all woody crop

60 wastes (Rosúa and Pasadas, 2012). It should be noted that, due to high

61 production, olive and wine industrial wastes are plentiful in Spain, but not

62 sufficiently valued. These two industries produce a large quantity of several

63 types of biomasses with different properties. Spain's Surfaces and Crop Yields

64 Inquiry (ESYRCE) shows an overall vineyard-crop cultivation area of 963,644

65 hectares, while the olive growing area amounts to 2,593,523 hectares, meaning

66 5.7% and a 15.1%, respectively, of overall cultivated surface area in Spain.

67 The main organic wastes obtained from the olive industry are olive pomace,

68 extracted olive pomace (coming from oil mills), olive vegetable water (also

69 called "alpechín"), a mixture of olive vegetable water and pulp (known as

70 "alperujo") and, in lower quantities, olive stones. Figures 1a and 1b show a

71 diagram of olive oil production using the three existing procedures and an

72 extractive plant flow chart.

73 The main organic wastes from the wine industry are pomace (pressed grape

74 waste), lees (fermentation and maturing precipitates), wine wash water

75 (vinasse), and the grape stalks that are separated in the destemmer. Figure 2

76 shows a white wine production chart, indicating wastes obtained in each phase

77 of production. Red wine production is slightly different, but the same types of

78 wastes are obtained.

79 Figures 1a, 1b and 2 illustrate olive and wine production wastes organized

80 according to colour. Thus, the green boxes are solid wastes, which are the

81 subject of interest in this work, while the liquids, which are not studied here,

82 appear in yellow. Finally, end or tail products for each process are marked in

83 blue, and sub-products and other wastes are marked in grey.

84 In addition to the woody crops, there are other biomass sources like the

85 harvesting of shrubland areas or of whole trees not necessarily coming from

86 agro-crops. The thinning out of wooded areas and the proper treatment of

87 shrubs is a useful tool for preventing disease while sustainably exploiting

88 Spain's woody regions. Olive groves, vineyards and orchards require regular

89 pruning, which generates a huge amount of biomass available for energy use

90 (Spinelli and Picchi, 2010).

91 On the other hand, extensive neglected scrubland zones are an undesirable

92 fuel source and the main spreader of forest fires in Spain, and they represent a

93　significant environmental impact because of adding to the greenhouse effect.

94　The valorization of these wastes could be an incentive for environmental clean-

95　up, considering that forestry biomass reaches 18,715,359 tonnes per year,

96　while the whole biomass potential in Spain alone reaches 88,677,193 tonnes

97　per year, as shown in Table 1.

98　In fact, not all of these waste materials are usually properly managed. For

99　example, prunings are commonly burned in the same place where they are

100　gathered (Velázquez-Martí et al., 2011). The energy use of these wastes not

101　only contributes to sustainable energy production, but also improves the

102　management of waste materials *in situ*.

103　Taking into account the lack of accurate biomass standardization, particularly in

104　terms of physicochemical, process and environmental indicators, the evaluation

105　and selection of raw materials for obtaining better process efficiencies presents

106　many difficulties. Therefore, a proper characterization is required for the

107　adequate use the wastes previously described.

108　The properties of commercial fuel are usually well known. Nevertheless, some

109　waste-biomasses, like the ones studied in this article, are not fully standardized

110　and do not follow any specific, existing normative (that for pellets, for example),

111　so it becomes necessary to study their characterization in depth. This research

112　group has previously developed studies on the proximate and ultimate analysis

113　of biomass fuels (García et al., 2014a, 2014b). A chemical composition study of

114　those materials is thus required in order to fully complete this work.

115   The main structural components of biomass are cellulose, hemicellulose and

116   lignin. Cellulose appears in the largest quantities in lignocellulosic biomass,

117   which is a linear polymer formed by ß-glucose units joined together by ß-1,4-

118   glucosidic bonds. In addition, as a whole, it possesses a fibrous structure in

119   which hydrogen-bridge bonds between hydroxyl groups of alternate glucose

120   chains are formed, making it tough and insoluble to water (Smook, 2002).

121   Hemicelluloses, as cellulose, are polymers made of pentoses, hexoses and

122   uronic acid units. They are smaller than cellulose and, also being amorphous

123   polysaccharides, each unit generally contains more than one kind of sugar

124   (Carrier et al., 2011).

125   Lignin is a 3D polymer formed by three units of phenylpropane (conipheryl,

126   sinapyl and coumaryl alcohols). Lignin possesses a huge variety of functional

127   groups and 10 different bond types (Tejado et al., 2007).

128   Figure 3 shows the 3D order of the main biomass chemical components as well

129   as the proportion in which they usually appear. The images were obtained using

130   a Scanning Electron Microscope (SEM), at a magnification of 110x, 250x and

131   130x for lignin, cellulose and hemicellulose, respectively.

132   In Figure 3, depicts how cellulose appears as long fibres surrounded by a net of

133   hemicellulose, joined by hydrogen-bridge bonds. Lignin is placed as a matrix

134   between the strings formed by the merging of cellulose and hemicellulose.

135   These fractions are joined by hydrogen-bridges and covalent bonds (benzyl

136   esters, benzyl ethers and phenyl glycosides (Smook, 2002)).

Chemical composition is closely related to the potential applications of a material and therefore to its energy use because higher heating value (HHV) greatly depends on these compounds. This relationship can be observed by the existence of varying HHV-predictive equations based on chemical composition.

The common methods for determining Lower Heating Values (LHV, defined as excluding heating losses through sub-products of combustion) and Higher Heating Values (HHV), may be classified into three inter-connected basic groups: theory, direct experimentation and empirical correlations. In fact, thermodynamic models based on rigorous state theories have the drastic inconvenience of needing detailed and precise analysis of all of the thousands of molecules present in such a natural product in order to reliably integrate (if previously available) a significant number of reactive internal energies or enthalpies. Experimentation must be carried out using original and sophisticated laboratory techniques or by precise, consolidated and commercially well-developed ones, e.g., by calorimetric bomb. Empirical estimations attempt to shortcut time-consuming experimental calculations, thus reaching the typical engineering compromise between requirements and accuracy. This question has been thoroughly discussed in some of our previous contributions (García et al., 2014a, 2014b).

The purpose of these last methods, particularly useful in a practical context, is to avoid slow and cumbersome procedures correlating HHV and LHV with less onerous available data (i.e., structural analysis is preferable to elemental analysis) while maintaining reliability within acceptable limits.

160 This work proposes several equations, based on experimentally obtained data,

161 which enlarge the inventory of equations previously proposed by other authors,

162 and which is summarized in Table 2.

163 As can be seen in Table 2, equations obtained after bibliographical review can

164 be categorized for specific biomass groups (like TIL or WHI, exclusively for

165 woody fuels) or with broad, general applicability. They can also be defined from

166 just one biomass fraction (like ACA or DEM01, 03 and 04) or from more than

167 one, such as J&G, which uses all structural biomass components in their

168 proposed correlation. In addition, fractions used to calculate HHV values may

169 be expressed on a different basis by different authors.

170 The new equations proposed here for estimating HHV are based on the

171 chemical structural analysis of biomass samples.

172

173 **2. Samples and methods**

174 2.1. Samples

175 Chemical composition and HHV were determined for twenty biomass samples

176 belonging to agro-forestry wastes and industrial wastes. For the purpose of

177 illustration, Figure 4 shows some of the analyzed samples.

178 As a pre-treatment to sort and isolate the analyzed fractions, all studied

179 samples were grinded and milled until particle size was in the range of 250-

180 500 µm (TAPPI, 2007).

181 2.2. Experimental procedure

182 Biomass chemical composition can be obtained through a chemical extraction

183 process that is summarized in Figure 5. Data for different fractions are

184 expressed on the basis of free dry, ash and extractives. Every experimental run,

185 except the singular extractive determinations, was performed three times to

186 assure reproducibility according to a pre-established accuracy.

187 2.2.1. Sample preparation

188 Before quantifying different biomass fractions, it was necessary to homogenize

189 sample size distribution. Once this was achieved, samples were subjected to a

190 two-stage extraction process to eliminate a group of substances known as

191 "extractives" that may interfere with a rigorous characterization. The first of

192 these stages consisted of an acetone treatment in a Soxhlet extractor lasting 7-

193 8 hours to get rid of resins, waxes, sterols, fats and fatty acids. The second

194 phase was carried out with boiling water for 1 hour: tannins, gums, sugars and

195 coloured matter were removed. Once both phases were completed, the refined

196 biomass was air-dried to reduce its moisture content to below 15 %.

197 2.2.2. Holocellulose fraction determination

198 This quantity was obtained from an extractive-free biomass using an acetic acid

199 and sodium chloride treatment, according to the ASTM D-1104 standard (Test

200 for Holocellulose in Wood) (ASTM International, 1978).

201 2.2.3. Cellulose fraction determination

202 Cellulose quantity was determined from the holocellulose fraction obtained

203 previously. This procedure consisted of a sodium hydroxide treatment according

204 to the TAPPI T 212 standard (TAPPI, 2002). Hemicellulose content can be

205 derived from the difference between holocellulose and cellulose quantities.

206 2.2.4. Lignin fraction determination

207 Lignin quantification was determined according to the NREL/TP-510-42618

208 standard (A. Sluiter et al., 2008), which consists of a two-stage acid hydrolysis,

209 with the first step using concentrated sulphur acid and the second stage with

210 the same diluted agent at high pressure.

211 2.2.5. Ash fraction determination

212 An ash quantification test, following the NREL/TP-510-42622 (A. Sluiter et al.,

213 2005) standard, was carried out. This procedure consists of a thermal treatment

214 of each fraction at 600º C for every previously calculated fraction.

215 2.2.6. HHV determination

216 The quantification of this energy content indicator was carried out using an IKA

217 Werke C5000 calorimetric bomb, and following the ASTM E711 (ASTM

218 International, 1987) standard. HHV data used in this article are shown in

219 Table 3.

220

221

222

3. Results and discussion

3.1. Structural Analysis

Analysis data obtained by chemical extraction for each studied sample are shown in Table 4. Contents of structural components are normalised to 100%.

Analysed samples demonstrate a wide range of extractive matter ratios, from 0.35% for chestnut tree chips, to 67% for extracted olive pomace. The variability in structural component quantity is not as wide. As expected, values between 21% and 39% were found for lignin, but grape stalk was exceptional with a value of over 50%. The range for cellulose was 27% to 60%, while for hemicellulose the indices obtained were between 10.68% for olive stone and 42.79% for corncob. The exception, once again, was grape stalk, which exhibited just 2%. These results were been compared with others available in the literature such as those of (Vassilev et al., 2012; Mendes et al., 2013; Prozil et al., 2012; Matos et al., 2010), and there is a notably strong agreement among them.

3.2. HHV estimations

The first step consisted of determining which of the parameters is the most influential on an HHV estimate. Matlab's command *corrcoef* was used for this purpose. R and P matrixes were obtained, with R being a squared matrix of correlation coefficients, with as many rows and columns as compared variables. The P matrix contains the P-values, and is the result of checking the non-correlation hypothesis. The results for the tested variables are shown in Table 5.

246 According to the statistical protocol, the closer to 0 a P-value comes, the higher

247 the probability of dependence there is between the correlated variables, so the

248 corresponding R-values can be considered significant. An examination of Table

249 5 shows that correlations obtained for cellulose demonstrate P-values much

250 higher than 0.05, so the relationship between HHV and this parameter is

251 meaningless. Therefore, no cellulose-based correlations have been proposed.

252 Nevertheless, the P-values obtained for lignin and hemicellulose were low, so

253 these fractions should be considered as important in determining HHV.

254 After choosing the most important parameters, the Matlab command *regress* is

255 used to obtain linear equations based on the selected parameters or linear

256 combinations thereof. The correlations thus obtained were statistically checked

257 using three criteria: *absolute average error* (AAE), *average bias error* (ABE),

258 relative errors commonly used by several authors (Callejón-Ferre et al., 2014;

259 Sheng and Azevedo, 2005) and *average absolute deviation* (AAD). They are

260 defined as follows:

261
$$\text{AAE (\%)} = \frac{1}{n}\left[\sum 100 \frac{|\text{HHV}_{\text{calc}}\text{-HHV}_{\text{exp}}|}{\text{HHV}_{\text{exp}}}\right] \tag{1}$$

262
$$\text{ABE (\%)} = \frac{1}{n}\left[\sum 100 \frac{(\text{HHV}_{\text{calc}}\text{-HHV}_{\text{exp}})}{\text{HHV}_{\text{exp}}}\right] \tag{2}$$

263
$$\text{AAD} = \frac{1}{n}\left[\sum|\text{HHV}_{\text{calc}}\text{-HHV}_{\text{exp}}|\right] \tag{3}$$

264

265 Proposed equations and their error values are shown in Table 6. Based on

266 structural analysis data, these equations show a lower value for AAE (1.13%)

267   compared to the AAE values of correlations based on proximate or elemental

268   analysis data (5% to 7%) proposed by the authors (García et al., 2014a,

269   2014b).

270   In Figure 6, the relationship between the predicted values (X-axis) and those

271   obtained experimentally (Y-axis) using data from the bibliography (Telmo and

272   Lousada, 2011; Demirbaş, 2001) are shown in order to validate the equations

273   proposed in this article.

274   As can be seen in Figure 6, all of the data are within a range of 13% of error

275   with respect to the experimental values.

276

277   **4. Conclusions**

278   Chemical analysis confirmed that the main component of lignocellulosic

279   biomass is cellulose (27% to 60%), followed by lignin (21% to 39%) and

280   hemicellulose (10% to 43%).

281   Results obtained and shown in this article are in good agreement with those

282   obtained by other authors.

283   Higher Heating Value is related to the content of biomass structural compounds,

284   mainly lignin. Existing equations for predicting HHV are focused on specific

285   biomass groups, while the ones proposed in this work have a general character.

286 The equations presented in this work depend on structural biomass

287 components, predicting HHV values with an average absolute error (AAE) of

288 less than 1.13%.

289

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307

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Figure captions

433 **Fig. 1a.** Olive oil production flowchart: olive oil mill (hydromechanical method)

434 **Fig. 1b.** Olive oil production flowchart: olive pomace extractor (mass transfer
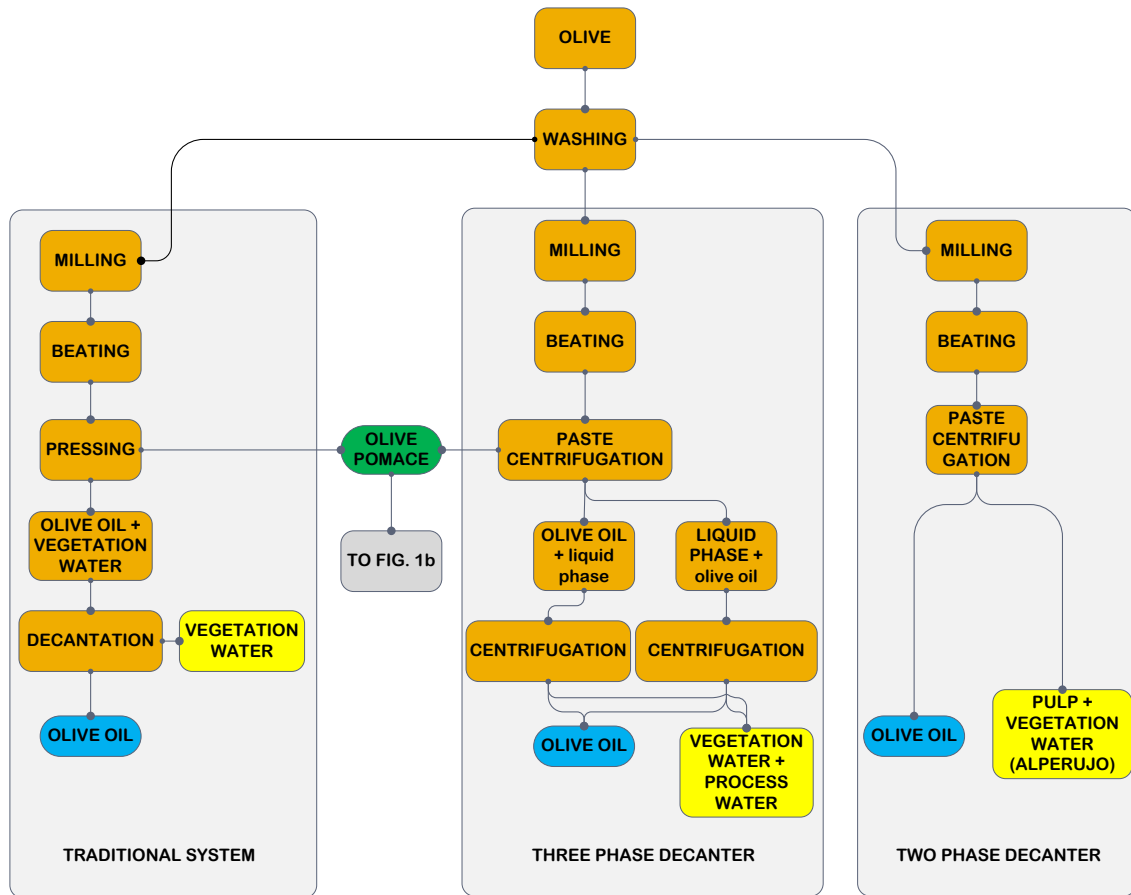
435 method)

436 **Fig. 2.** White wine production flowchart

437 **Fig. 3.** 3D biomass structure

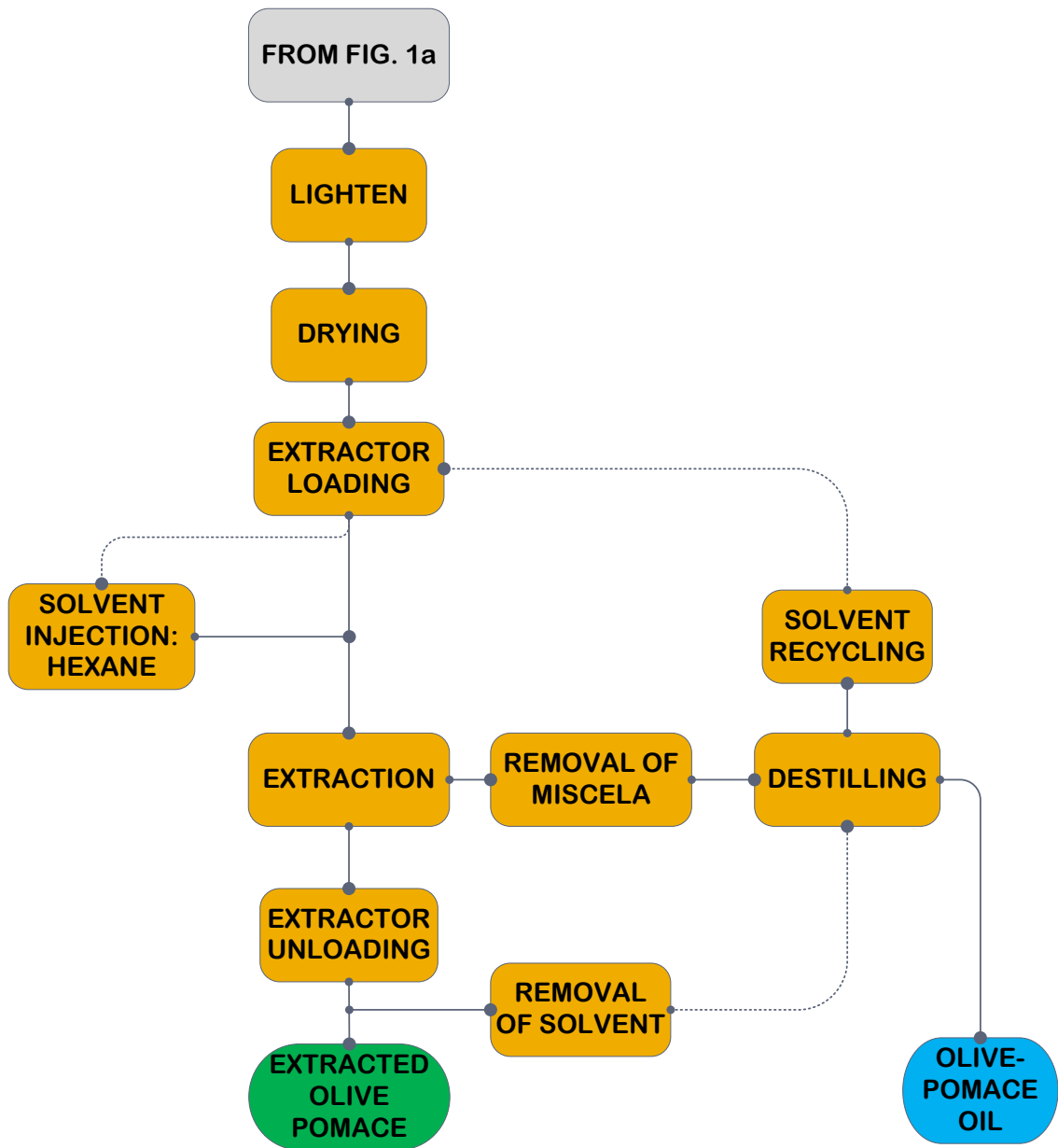438 **Fig. 4.** Pictures of the samples analysed

439 **Fig. 5.** Experimental procedure chart

440 **Fig. 6.** Predicted vs. experimental HHV from data in the bibliography

OLIVE

WASHING

TRADITIONAL SYSTEM
- MILLING
- BEATING
- PRESSING
- OLIVE OIL + VEGETATION WATER
- DECANTATION → VEGETATION WATER
- OLIVE OIL

OLIVE POMACE
- TO FIG. 1b

THREE PHASE DECANTER
- MILLING
- BEATING
- PASTE CENTRIFUGATION
- OLIVE OIL + liquid phase
- LIQUID PHASE + olive oil
- CENTRIFUGATION
- CENTRIFUGATION
- OLIVE OIL
- VEGETATION WATER + PROCESS WATER

TWO PHASE DECANTER
- MILLING
- BEATING
- PASTE CENTRIFUGATION
- OLIVE OIL
- PULP + VEGETATION WATER (ALPERUJO)

441

Fig. 1a. Olive oil production flowchart: olive oil mill (hydromechanical method).

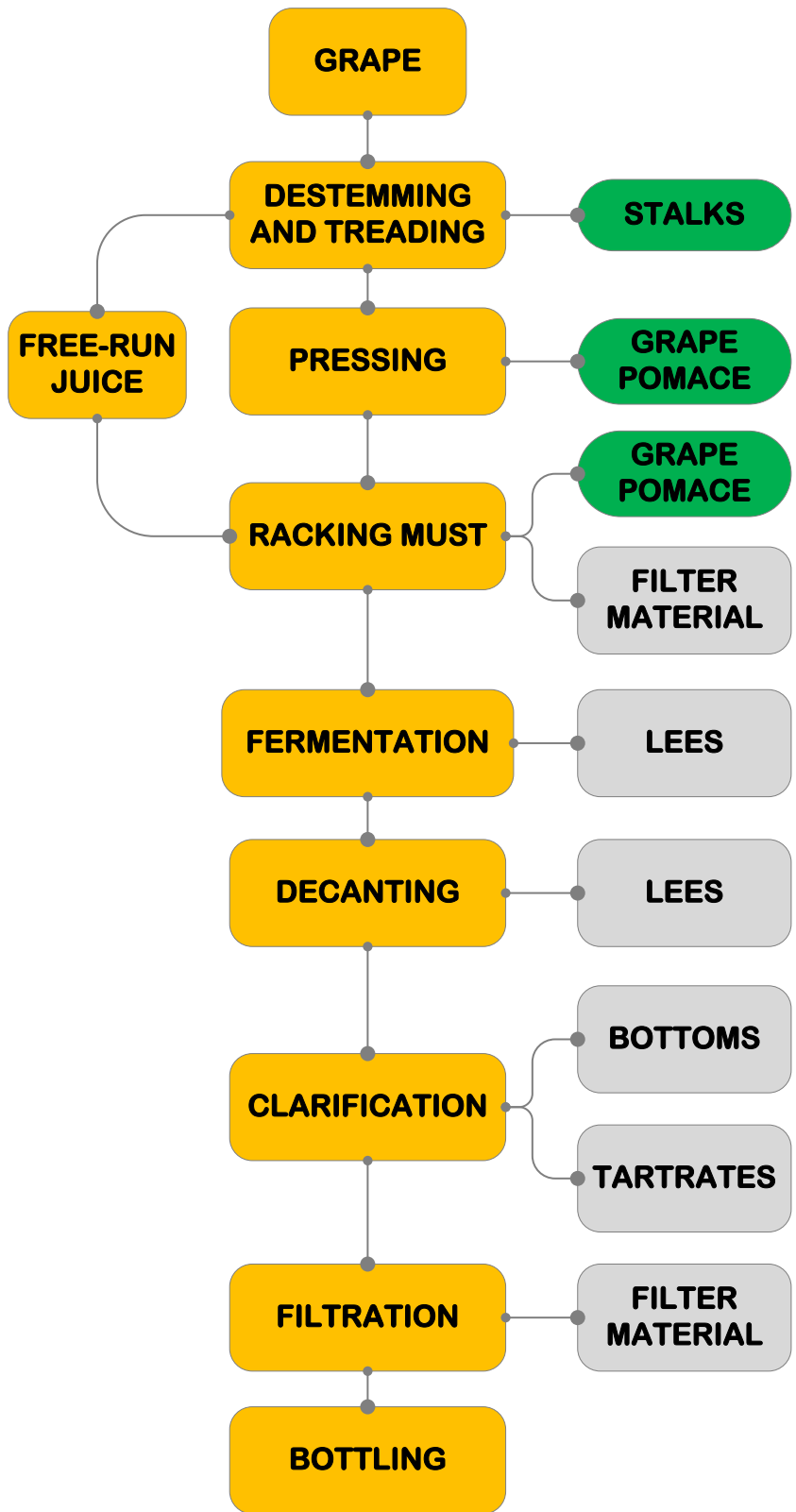**Fig. 1b.** Olive oil production flowchart: olive pomace extractor (mass transfer method).

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Fig. 2. White wine production flowchart.

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448

Lignin

Hemicellulose

Cellulose

15-25%

45-50 %

15-30%
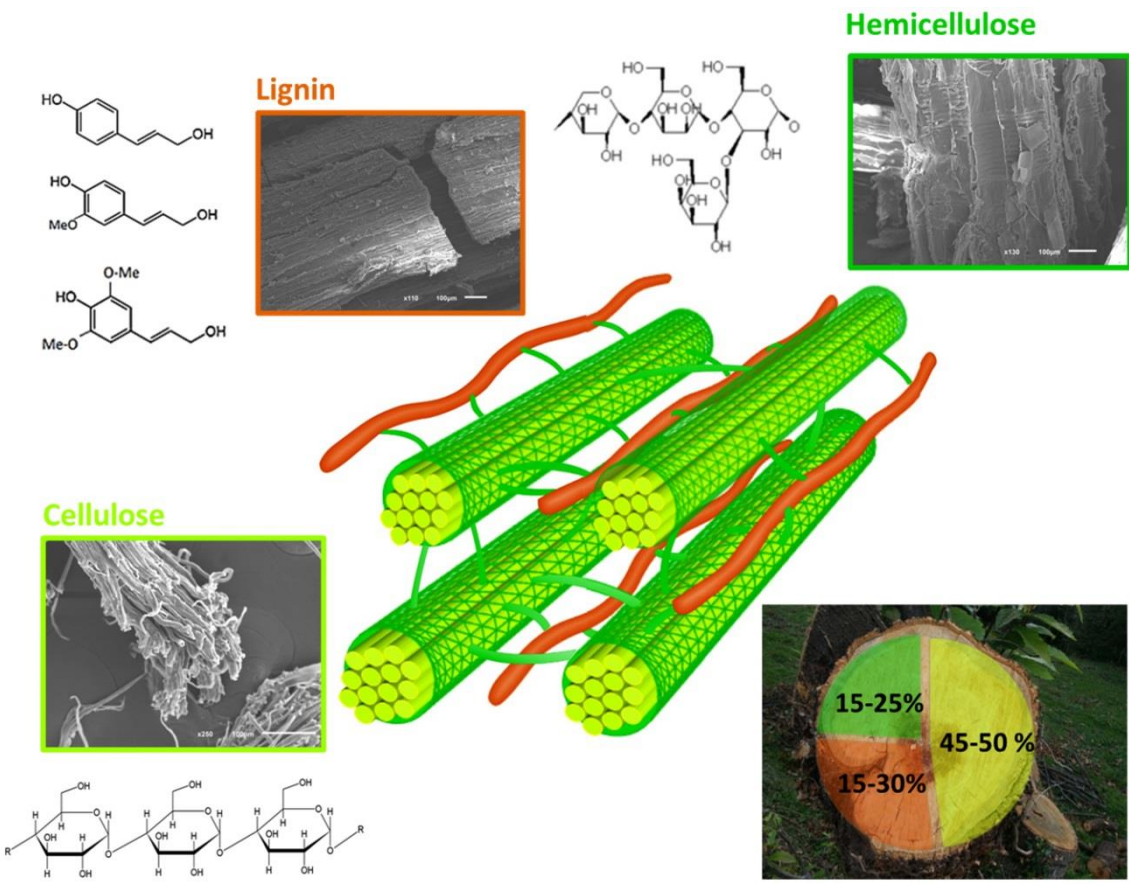
449

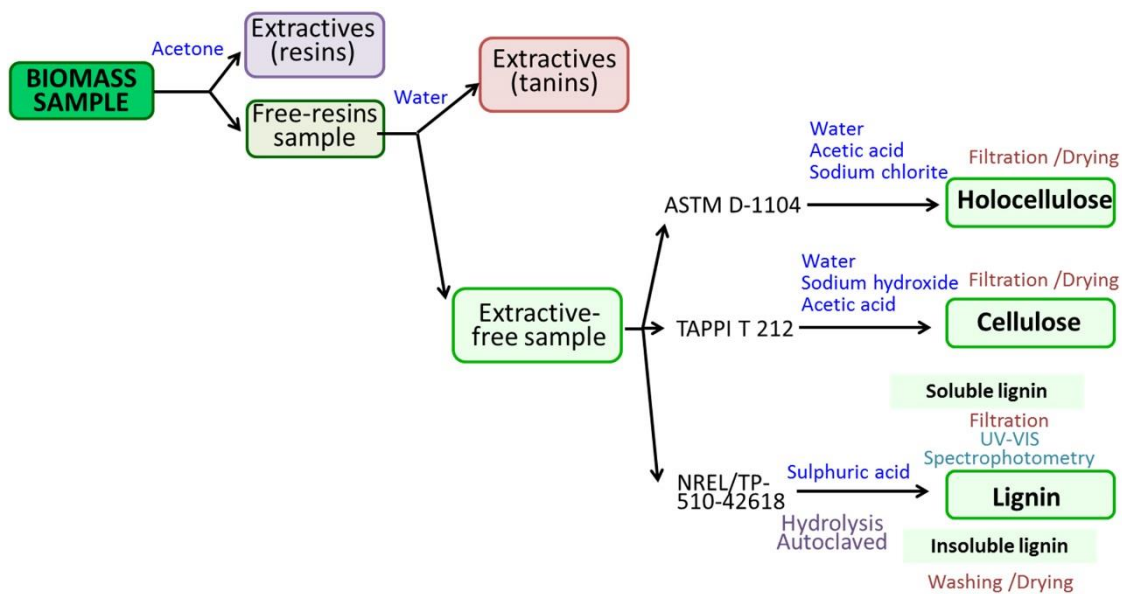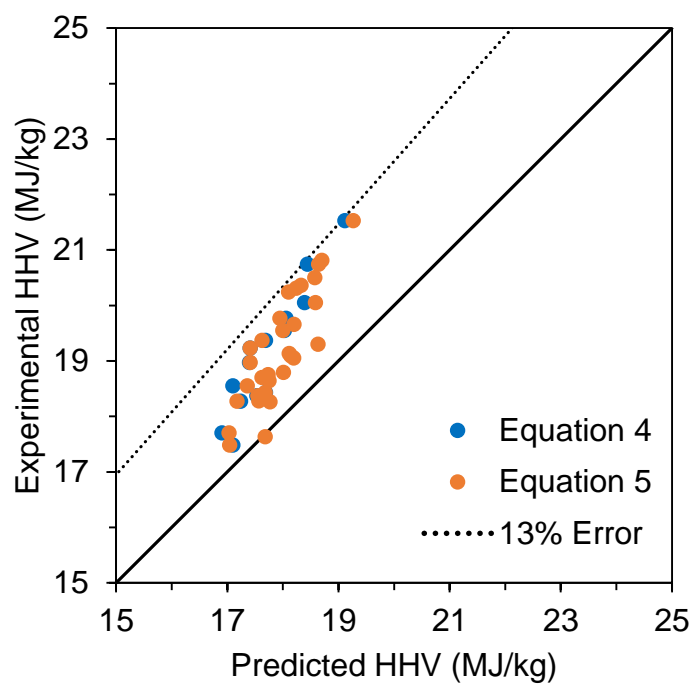450   **Fig. 3.** 3D biomass structure
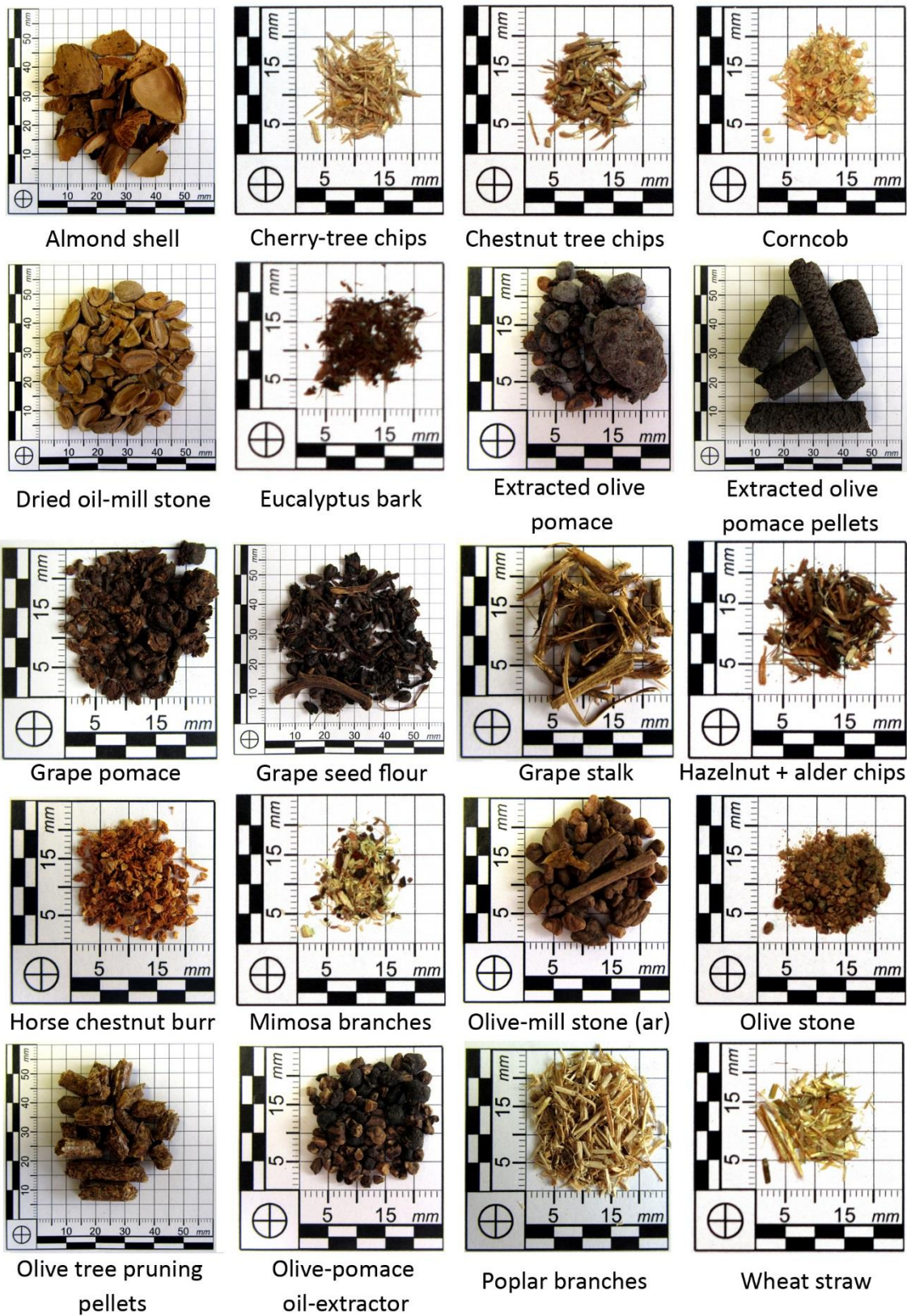
Fig. 4. Pictures of the samples analysed.

453

454 **Fig. 5.** Experimental procedure chart.

455

Fig. 6. Predicted vs. experimental HHV from data in the bibliography.

457 **Table 1.** Available potential biomass (t/year) and average production cost (€/t)

458 in Spain (IDAE, 2007)

Origin		Biomass (t/year)	Biomass (tep/year)	Average costs (€/t)
Existing forest areas	Wood harvesting remains	2 984 243	636 273	25.59
	Whole tree harvesting	15 731 116	3 414 158	43.16
Agricultural residues	Herbaceous Woody	14 434 566 16 118 220	6 392 631	20.97
Herbaceous biomass susceptible to implementation in agricultural land		14 737 868	3 593 148	53.39
Woody biomass susceptible to implementation in agricultural land		6 598 861	1 468 173	36.26
Woody biomass susceptible to implementation in forest land		15 072 320	1 782 467	42.14
Total potential biomass in Spain		**88 677 193**	**17 286 851**	

459

460

461 **Table 2.** Structural composition-based models (Callejón-Ferre et al., 2014).

AUTHOR	CORRELATION (HHV, MJ/kg dry basis)	COMMENTS
S&D (Shafizadeh et al., 1976)	HHV=0.17389[Ce]+0.26629[L]+0.32187[E]	Lignocellulosic biomass.
TIL (Tillman, 2012)	HHV=0.17389[Ce]+0.26629(100-[Ce*])	Woody biomass.
WHI (White, 1987)	HHV=17.9017+0.07444[L*]+0.0661[E*][a]	Not extracted wood. Neither R^2_{ajust}, not SE available
	HHV = 17.6132 + 0.0853[L*][a]	Extractive free wood. Neither R^2_{ajust}, not SE available
	HHV = 17.4458 + 0.0907[L*][a]	Extractive free softwood. Neither R^2_{ajust}, not SE available
	HHV = 18.0831 + 0.0637[L*][a]	Extractive free hardwood. Neither R^2_{ajust}, not SE available
	HHV = 17.7481 + 0.0800[L*](100-[E])/100 + 0.0886[E][a]	Not extracted wood. Neither R^2_{ajust}, not SE available
J&G (Jiménez and González, 1991)	HHV=(1-[Ash]/([Ce] + [L] + [E]))(0.17389[Ce] + 0.26629[L] + 0.32187[E])	Vegetal biomass. Neither R^2_{ajust}, not SE available
DEM$_{01}$ (Demirbaş, 2001)	HHV**=0.0889[L**] + 16.8218	Vegetal biomass. SE not available
	HHV**=0.0893[L**] + 16.9742	Wood and bark. SE not available
	HHV**=0.0877[L**] + 16.4951	Not woody vegetal biomass. SE not available
DEM$_{02}$ (Demirbas, 2002)	ΔHHV = 0.00639[E]2 + 0.223[E] + 0.691	Vegetal biomass. SE not available.
DEM$_{03}$ (DEMİRBAŞ, 2003)	HHV**=0.0864[L**] + 16.6922	Bark and shell. SE not available
DEM$_{04}$ (Demirbas, 2004)	ΔHHV = 0.383[E]-0.0387	Vegetal biomass. Neither R^2_{ajust}, not SE available
ACA (Acar and Ayanoglu, 2012)	HHV = 0.0979[L] + 16.292	Vegetal biomass. SE not available

Ce: cellulose + hemicellulose; L: lignin; E: extractive both measured in dry basis percentage

* Indicates composition (%) in dry and extractive free basis.

 ** Indicates composition (%) in dry ash free and extractive free basis.

Not SE: not standard error available.

[a] These correlations can be converted to MJ/kg as: 1 Btu/lb = 2,3261x10^{-3} MJ/kg.

462   Table 3. HHV data used in this article (García et al., 2014a) and (García et al.,

463   2014b).

Sample	HHV (kJ/kg)
Almond shell	18.275
Cherry-tree chips	17.595
Chestnut tree chips	17.485
Corncob	17.344
Dried oil mill stone	18.092
Eucalyptus bark	17.752
Extracted olive pomace	18.186
Extracted olive pomace pellets	18.182
Grape pomace	17.019
Grape seed flour	16.467
Grape stalk	18.809
Hazelnut +alder chips	17.555
Horse chestnut burr	17.165
Mimosa branches	16.237
Oil-mill stone (ar)	16.484
Olive stone	17.884
Olive tree pruning pellets	18.720
Olive-pomace oil-extractor	18.687
Poplar branches	18.411
Wheat straw	17.692

464

465   **Table 4.** Chemical composition of biomass samples obtained by chemical

466   extraction.

Sample	E[a]	HoloC[b]	C[b]	HemiC[b]	I.L.[b]	S.L.[b]
Almond shell	8.02	69.12	55.07	14.05	28.37	2.51
Cherry-tree chips	1.88	75.64	46.51	29.13	22.13	2.23
Chestnut tree chips	0.35	72.61	43.39	29.22	24.74	2.65
Corncob	8.72	72.50	29.71	42.79	24.49	3.02
Dried oil mill stone	2.30	72.61	50.31	22.30	25.79	1.61
Eucalyptus bark	11.30	65.73	37.31	28.42	32.37	1.90
Extracted olive pomace	67.79	57.27	27.60	29.67	38.89	3.84
Extracted olive pomace pellets	55.96	62.58	31.05	31.53	34.25	3.17
Grape pomace	26.06	46.76	28.83	17.93	51.74	1.50
Grape seed flour	9.82	53.55	37.75	15.80	45.54	0.91
Grape stalk	39.34	46.37	43.97	2.40	51.80	1.83
Hazelnut +alder chips	12.30	65.84	34.77	31.08	31.92	2.23
Horse chestnut burr	43.66	62.85	44.82	18.03	36.05	1.11
Mimosa branches	16.81	68.68	40.18	28.51	29.76	1.56
Oil-mill stone (ar)	7.99	71.96	44.72	27.24	26.51	1.53
Olive stone	2.98	69.61	58.93	10.68	28.64	1.75
Olive tree pruning pellets	13.51	71.47	59.05	12.42	27.55	0.98
Olive-pomace oil-extractor	36.84	68.24	38.20	30.04	29.31	2.45
Poplar branches	8.02	72.97	46.16	26.81	25.63	1.40
Wheat straw	25.70	75.73	38.56	37.17	21.71	2.56

467   **Table 5.** P and R coefficients matrix (chemical extraction and TG).

R matrix			
HHV	Lignin	Hemicellulose	Cellulose
1.0000	0.8291	-0.6686	0.0740
P matrix			
HHV	Lignin	Hemicellulose	Cellulose
1.0000	0.0009	0.0175	0.8191

468

469 **Table 6.** Equations based on chemical composition.

	Equation	AAE (%)	ABE (%)	AAD
4	HHV=17.0704+0.0449·L-0.0202·H	0.87	0.02	0.15
5	HHV=16.1964+0.0555·L	1.13	0.02	0.20

L: lignin; H: hemicellulose (measured in mass percentage in dry ash and extractives free basis); HHV: higher heating value (MJ/kg in dry basis).

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