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# Upcycling Sunflower Stems as Natural Fibers for Biocomposite Applications

Jean-Denis Mathias,<sup>a,\*</sup> Arnaud Alzina,<sup>b</sup> Michel Grédiac,<sup>c,d</sup> Philippe Michaud,<sup>c,d</sup> Philippe Roux,<sup>e</sup> Hélène De Baynast,<sup>c,d</sup> Cédric Delattre,<sup>c,d</sup> Nicolas Dumoulin,<sup>a</sup> Thierry Faure,<sup>a</sup> Pyrène Larrey-Lassalle,<sup>c</sup> Narimane Mati-Baouche,<sup>c,d</sup> Fabienne Pennec,<sup>b</sup> Shengnan Sun,<sup>c,d</sup> Nicolas Tessier-Doyen,<sup>b</sup> Evelyne Toussaint,<sup>c,d</sup> and Wei Wei<sup>a</sup>

One of the big global, environmental, and socioeconomic challenges of today is to make a transition from fossil fuels to biomass as a sustainable supply of renewable raw materials for industry. Growing public awareness of the negative environmental effects of petrochemical-based products adds to the need for alternative production chains, especially in materials science. One option lies in the value-added upcycling of agricultural by-products, which are increasingly being used for biocomposite materials in transport and building sector applications. Here, sunflower by-product (obtained by grinding the stems) is considered as a source of natural fibers for engineered biocomposite material. Recent results are shown for the main mechanical properties of sunflower-based biocomposites and the socioeconomic impact of their use. This paper demonstrates that sunflower stem makes a good candidate feedstock for material applications. This is due not only to its physical and chemical properties, but also to its socioeconomic and environmental rationales.

*Keywords:* Agricultural by-product; Biocomposite; Natural fiber; Sunflower stem; Waste management

*Contact information:* a: IRSTEA, Laboratoire d'Ingénierie pour les Systèmes Complexes, 9 avenue Blaise Pascal, CS 20085, 63178 Aubière, France, b: GEMH-CEC, 12, rue Atlantis, 87068 Limoges Cedex, France, c: Institut Pascal, Clermont Université, Université Blaise Pascal, BP 10448, F-63000 Clermont-Ferrand, France d: CNRS, UMR 6602, Institut Pascal, 63177 Aubière Cedex, France e: IRSTEA, UMR ITAP, 361 rue Jean-François Breton, BP5095, 34196 Montpellier cedex 5, France;

\* Corresponding author: jean-denis.mathias@irstea.fr

## INTRODUCTION

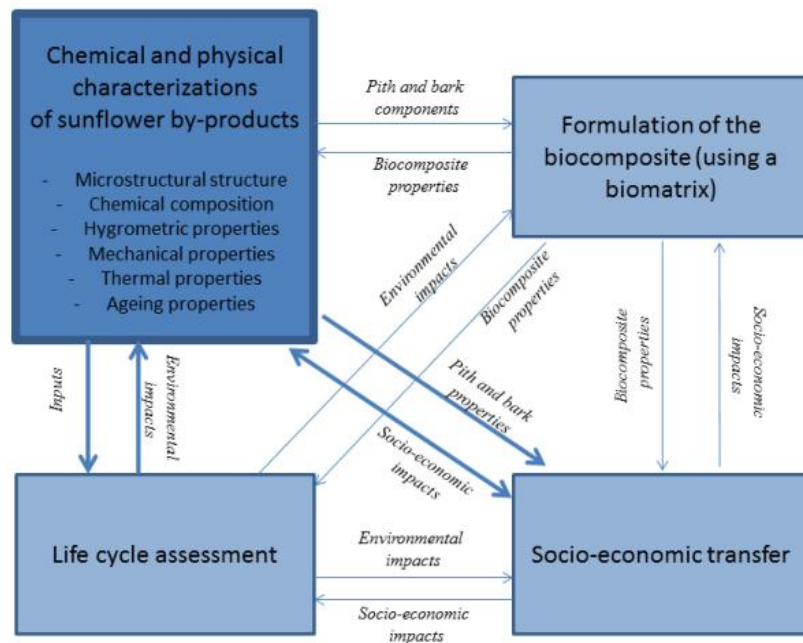
Over the last few decades, increasing environmental concerns have prompted a surge in research by the composite science community to develop natural-fiber biocomposites. These materials can be completely degraded in soil, or, by composting, do not emit volatile organic compounds, and are softer on the environment than petrochemical resource-based products (Mohanty *et al.* 2000; Lithner *et al.* 2011). Agricultural by-products have several advantages over classical natural fibers: they do not need dedicated agricultural fields, they are already readily available, and they offer valuable environmental compatibility over standard-feedstock fibers (Reddy and Yang 2005). These factors are increasingly central now that biocomposites have found widespread use in all areas of life. The reason for this increasing use of biocomposites is performance at lower cost and reduced density when compared to classic synthetic materials (Reddy and Yang 2005). Nonetheless, some agricultural by-products are already exploited by second-generation biorefineries (Pfaltzgraff and Clark 2014).

52 Therefore, the main objective for the bio-based material sector now is to find new sources  
53 of fibers to avoid competition with the growth of crops for human food or biofuels  
54 (Kopetz 2013). In this context, the present work focuses on a promising agricultural by-  
55 product, sunflower stems. Sunflower by-products are of interest because they are not  
56 currently exploited, their composition enables low-impact extractability from the field,  
57 and oilseed biorefineries can achieve greater economic viability by selling their by-  
58 products.

59 Sunflower-based oil ranks fourth in world oil crop production, with nearly 25  
60 million hectares (FAOSTAT 2013). Seed and oil have been the main compounds  
61 exploited by industry. In most cases, seed and oil are both extracted from the head, and  
62 the stems are left in the fields. No significant industrial use of the stems that are shredded  
63 after seed harvesting has currently been proposed, although sunflower stems are exploited  
64 for combustion applications, animal feed, and/or fuel production (Chen and Lu 2006).  
65 These solutions consume only a small fraction of the sunflower by-product production.  
66 We propose to explore a new way of extracting value from sunflower stems by evaluating  
67 their potential as a natural fiber feedstock for biocomposite applications. Considering five  
68 tons of sunflower stalks per hectare, the potential production of this by-product reaches  
69 125 million tons. In comparison with other natural fibers (not including wood), this  
70 potential production tonnage is higher than that of bamboo farming (30 million tons,  
71 mostly in Asia and South America), which, alongside cotton, is one of the most heavily  
72 produced sources of commercial fiber in the world (Faruk *et al.* 2012). The potential  
73 value of sunflower by-products as a biofiber is enhanced by the fact that sunflower is  
74 grown worldwide (FAOSTAT 2013). This could create opportunities to build a new  
75 worldwide agricultural economy and is a key advantage over other agricultural by-  
76 products, like bamboo, that are not available across the world. Furthermore, sunflower  
77 by-products are available in large amounts at zero or negligible price in an economic  
78 context, where the natural-fiber biocomposites market grew by 15% between 2005 and  
79 2010 (Lucintel 2011). Indeed, the entire composite market is growing. For example, the  
80 polymer composites market has increased from 33 billion Euros in 2002 to 41.5 billion  
81 Euros in 2005 (Friedrich and Almajid 2013). This surge in the natural fibers market is  
82 primarily driven by the automotive and building sectors (John and Thomas 2008). In the  
83 automotive sector, EU and US legislations impose specific directives on the end-of-life of  
84 vehicles. For instance, the non-recycled fraction of materials will be cut by 5% in 2015 in  
85 Europe (European Commission. Directive 2000/53/EC 2000). In addition, natural fibers  
86 are expected to provide a 30% weight reduction and a 20% cost reduction compared to  
87 classic composites (Bledzki *et al.* 2006). Furthermore, the low density of natural fibers  
88 equates to significant energy savings (primarily fuel) and their economic value may be  
89 extended to all fields of transportation (railway, marine, aerospace) (Bledzki *et al.* 2006;  
90 Friedrich and Almajid 2013). Natural fibers are also exploited in building applications,  
91 not only for their low density but also for their thermal insulating properties. Their  
92 development was recently stimulated in the USA and in Europe by legislation imposing  
93 enhanced energy efficiency of existing buildings by 2020 (European Commission.  
94 Directive 2010/31/EU 2010), which yielded a significant market in green retrofit  
95 solutions.

96 This work presents the main results obtained from a project (Demether 2011)  
97 whose objective was to produce biocomposites for building insulation by factoring not  
98 only chemical and physical properties but also the environmental and socio-economic  
99 impacts tied to processing and use (Fig. 1). In view of the results obtained, it is argued

100 that sunflower stems can be useful for other biocomposite-using applications such as  
 101 automobiles. First, general results are presented corresponding to sunflower by-product  
 102 properties, highlighting both unpublished and published data by giving associated  
 103 references. Note that examples of biocomposite engineering using sunflower by-products  
 104 can be found elsewhere (Mati-Baouche *et al.* 2014, 2015; Sun *et al.* 2015). In this  
 105 context, the objective here was twofold: i) to report the main results of the project about  
 106 the properties of the sunflower stems; ii) to report the general project conclusions on the  
 107 use of sunflower by-products to give the interested reader a clear picture of what can be  
 108 expected from this innovative type of biocomposite.



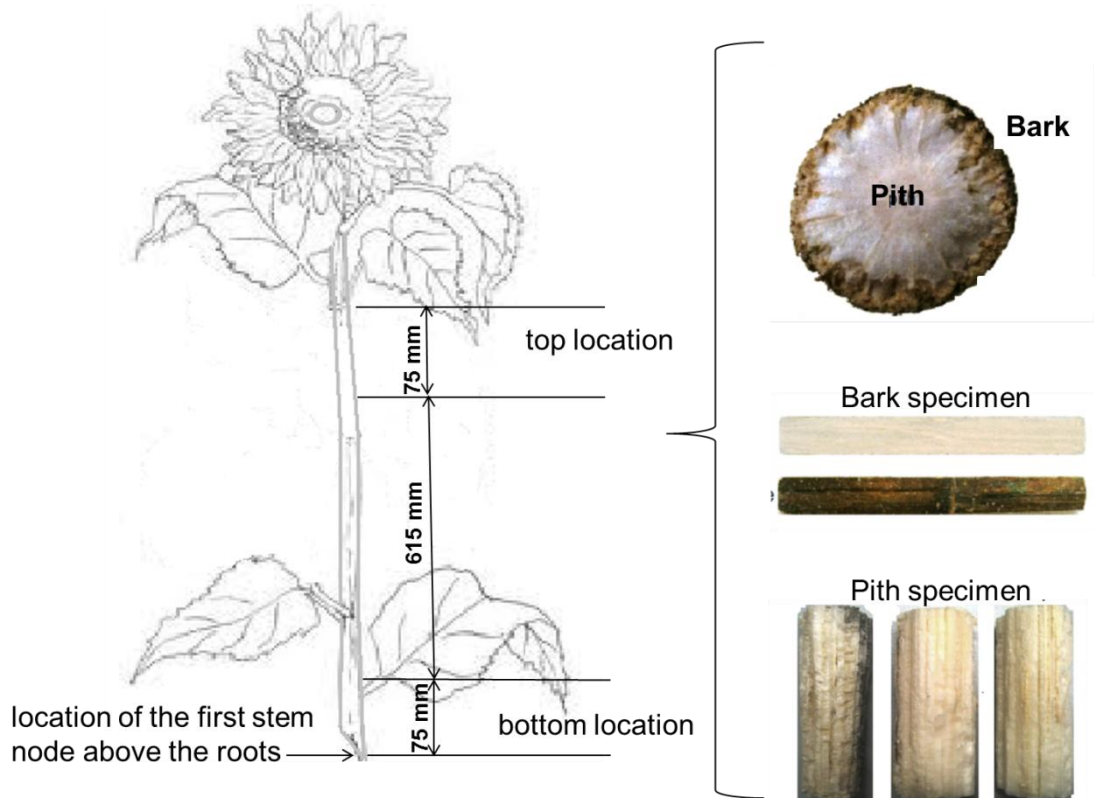
109  
 110 **Fig. 1.** General flowchart of the design of insulating biocomposite. The article focuses on the  
 111 main physical and chemical properties of sunflower stems obtained under this project framework.  
 112

## 113 EXPERIMENTAL

### 114 Sample Description

115  
 116 This study characterized the material properties of the stems of LG5474  
 117 sunflower species harvested in September 2010 in Perrier, France. Two particular on-  
 118 stem locations were defined as the bottom and the top of the stalk (Fig. 2). The bottom  
 119 location was defined as the level of the first node above the roots. Note that no specific  
 120 (mechanical or chemical) treatment was performed, as it has been shown that specific  
 121 treatments may alter certain properties (Li *et al.* 2007), as will also be shown by results  
 122 presented in the discussion that follows. However, as explained earlier, this paper focuses  
 123 on the properties of fibers, and any investigation into the influence of mechanical or  
 124 chemical treatments would require a dedicated companion paper. Evidence that these  
 125

126 fibers are useable without any particular treatment can be found elsewhere (Mati-  
 127 Baouche *et al.* 2014; Sun *et al.* 2015).  
 128



129  
 130 **Fig. 2.** Sampling zones and specimens tested  
 131

### 132 **Microstructural Analysis**

133 Sections of bark were first separated from the stem, saturated with water,  
 134 immersed, and kept in three PEG (polyethylene glycol electrolyte) solutions at various  
 135 concentrations (30%, 60% and 100%) for 24 h each. A 20  $\mu\text{m}$ -thick sample was cut using  
 136 a fully automated Leica (Wetzlar, Germany) RM2255 rotary microtome. It was then  
 137 colored with the so-called double-staining method using safranin (for the presence of  
 138 lignin) and astra blue (for the presence of cellulose). After coloration, the samples were  
 139 dried with Joseph paper. They were mounted on a cover-slip with the fast-drying Eukitt  
 140 (Freiburg, Germany) mounting medium. Finally, micrographs of these cross-sections  
 141 were obtained using a Zeiss (Oberkochen, Germany) optical microscope. These images  
 142 were processed with the ImageJ software (National Institutes of Health, USA) to estimate  
 143 the porosity of the barks extracted from both the bottom and top locations. Macroscopic  
 144 voids in the pith make it difficult to separate pith and bark. Therefore, the analysis should  
 145 be carried out on complete stem sections. The analysis was performed using the Skyscan  
 146 (Anvers, Belgique) CT-Analyzer with two sections of stem extracted from the bottom  
 147 and top locations. The working length was 30 mm.  
 148

### 149 **Cellulose and Lignin Assays**

150 A biochemical analysis was performed on bark of different stem specimens at  
 151 different locations (bottom, centre, and top). For the pith, cellulose and lignin assays were  
 152 applied without distinction of in-stem location. The Henneberg protocol (Henneberg and

153 Stohmann 1860, 1864) was used to quantify the percentage of cellulose (C). Lignin  
154 content (L) was evaluated by the procedure of Jarrige (Jarrige 1961).  
155

### 156 **Hygrometric Analysis**

157 Absorption and desorption tests were performed at various relative humidities  
158 (RH) (8%, 33%, and 75%) to deduce both the absorption and desorption coefficients. A  
159 desiccant (phosphorus pentoxide) was placed in the oven beforehand. The specimens  
160 were then placed in a conditioning chamber (one for each desired value of RH). These  
161 chambers were polymer jars in which saturated aqueous salt solutions imposed a certain  
162 RH. The RH depends on the nature of the salt. Absorption and desorption coefficients  
163 were deduced from the mass-time curves using suitable relationships that depend on  
164 specimen geometry. The different solutions corresponding to different RH levels were  
165 prepared according to standard ISO 483 procedure (2005). These tests lasted at least three  
166 days to ensure that equilibrium was obtained within the specimens. Six bark specimens  
167 and five pith specimens were tested for each experimental condition. See Sun *et al.*  
168 (2013, 2014) for further details.  
169

### 170 **Mechanical Analysis**

171 Results for bark specimens were obtained using a Deben (Suffolk, UK) micro-  
172 machine equipped with a 2-kN load cell. The cross-head speed was 2 mm/min with a  
173 clamping length of 30 mm. Results for pith specimens were obtained by compression  
174 tests using an Instron (Norwood, USA) 5543 testing machine equipped with a 500-N load  
175 cell. The cross-head speed was 5 mm/min. Ten specimens were tested for each  
176 experimental condition.  
177

### 178 **Thermal Analysis**

179 The thermal diffusivities of the bark and pith specimens were measured with the  
180 laser flash method. The specific heat capacity was measured with a C80 Setaram  
181 (Caluire, France) calorimeter. Finally, the thermal conductivity of the bark and pith  
182 specimens was deduced by multiplying apparent density (equal to the mass divided by  
183 the volume of cylindrical specimens) by thermal diffusivity and heat capacity. Another  
184 transient technique (Hot Disk from ThermoConcept, France) was used to check the  
185 thermal conductivity values on pith specimens and yielded similar results. Six samples  
186 were tested for each experimental condition.  
187

### 188 **Ageing Analysis**

189 Three weather conditions were tested: humidity, temperature, and UV radiation.  
190 The humidity and temperature values used for the ageing analysis were 75% and 80 °C,  
191 respectively. Specimens were tested for the ageing conditions of 75% humidity, 80 °C,  
192 and the combination of both. The ageing condition of 75% humidity was achieved  
193 according to the procedure given in the ISO 483 (2005) standard. Conditioning at 80 °C  
194 was performed using a Salvislab Thermocenter oven (Rotkreuz, Switzerland). The  
195 combined conditions were obtained using a Vötsch (Hanau, Germany) VCL 4003  
196 climatic oven. The UV exposure (1000 h) was performed in the accelerated conditions  
197 given by the Atlas MTT (Mount Prospect, USA) SEPAP 12 – 24 chamber, which  
198 corresponds to the ageing condition described in the usual standards on this subject (NF-  
199 T51-195-5 2008; BS EN 16472 2014).  
200

## 201 Spectroscopic Analysis

202 Fourier-Transform Infrared (FT-IR) measurements were carried out using a  
 203 Thermo Scientific (Waltham, Massachusetts) Nicolet 6700 FT-IR instrument. The IR  
 204 spectra (128 scans) were recorded at room temperature on a MTEC (Ames, USA) 200  
 205 photoacoustic detector (referenced against carbon black powder; detector chamber was  
 206 purged with dry helium gas) with a wave-number range of 700 to 4000  $\text{cm}^{-1}$ . The spectra  
 207 were analyzed with Thermo Scientific (Waltham, Massachusetts) Omnic software. Six  
 208 bark specimens and four pith specimens from the bottom and top locations were tested.

## 210 Environmental Assessment

211 For the comparison of environmental impacts between maize and sunflower,  
 212 EcoInvent data for crop production (Nemecek and Kagi 2007) was used. The endpoint  
 213 impacts (Goedkoop *et al.* 2009) associated with the production of maize grain and  
 214 sunflower seeds in one hectare (Nemecek and Kagi 2007) were compared, *i.e.*,  
 215 9279 kg/ha for maize and 3151 kg/ha for sunflower. The farming system considered here  
 216 was integrated production (IP). Included processes were soil cultivation, sowing, weed  
 217 control, fertilization, pest and pathogen control, harvesting, and drying the grains.  
 218 Machine infrastructure and a shed for housing the machine were included. Inputs of  
 219 fertilizers, pesticides, and seed, as well as their transport to the regional processing centre  
 220 (10 km), were considered.

## 223 RESULTS AND DISCUSSION

225 Obtained results are detailed and analyzed in the following sections. However, for  
 226 the sake of clarity, the main results are reported schematically in Fig. 3. The pith and bark  
 227 properties are compared with those of other natural fibers in Table 1.

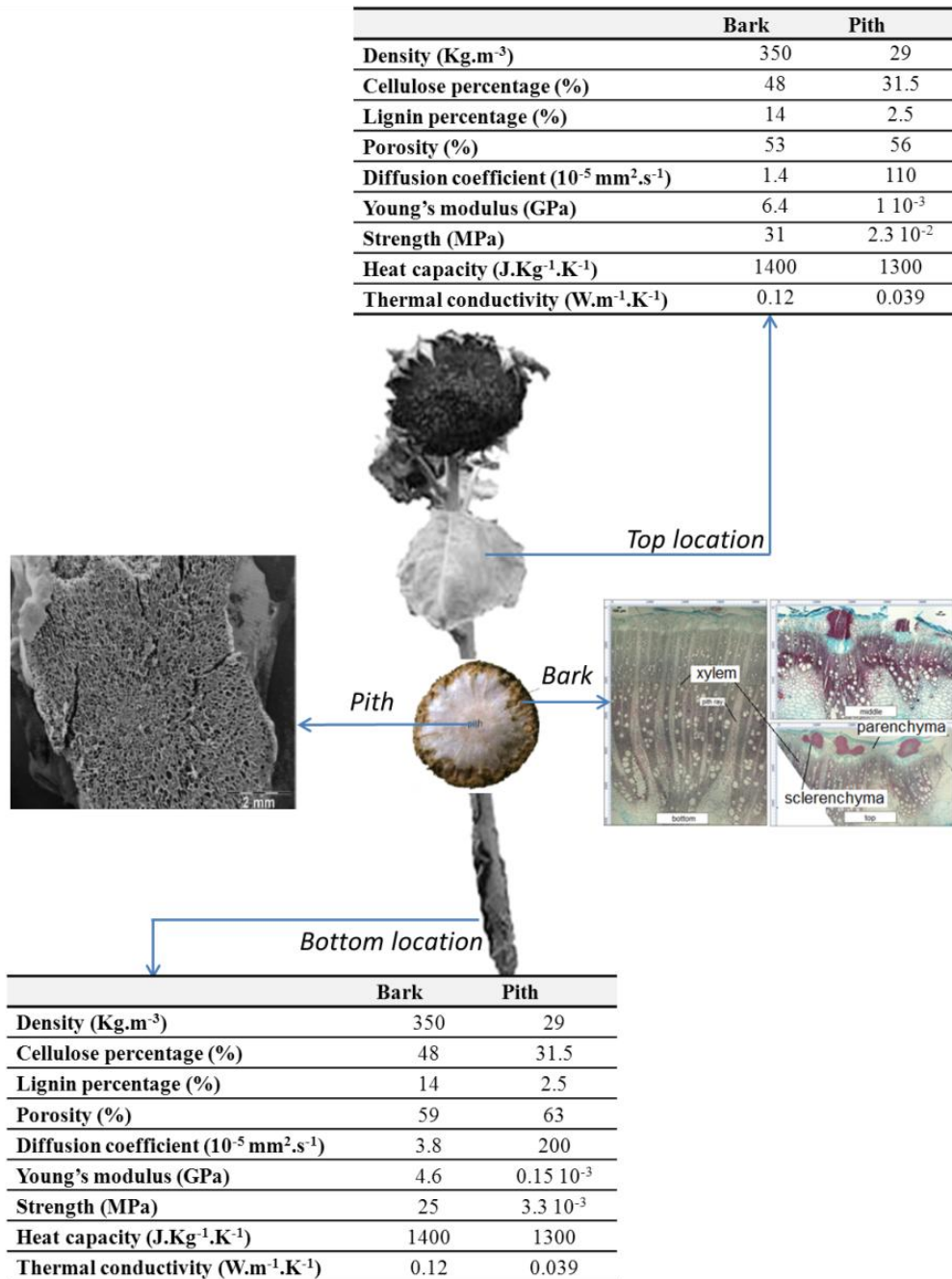
229 **Table 1.** Main Properties of Bark, Pith, and Other Natural Fibers

	Bark	Pith	Other natural fibers	References
Young modulus (GPa)	[4.6-6.4]	[0.15-1]. $10^{-3}$	Pineapple : 1.4 Oil palm: 3.2 Jute: 10 Flax: 80	(Faruk <i>et al.</i> 2012) (Faruk <i>et al.</i> 2012) (Ahmad <i>et al.</i> 2015) (Ahmad <i>et al.</i> 2015)
Specific modulus (GPa.m <sup>3</sup> .Kg <sup>-1</sup> )	[0.013-0.018]	[0.005-0.034]. $10^{-3}$	Coir : [0.0033-0.005] Jute: [0.00685-0.0206] Flax: [0.0184-0.053]	(Ahmad <i>et al.</i> 2015)
Strength (MPa)	[25-31]	[3.3-23]. $10^{-3}$	Coir : 175 Jute : [393-800] Flax: [800-1 500]	(Ahmad <i>et al.</i> 2015)
Thermal conductivity (W.m <sup>-1</sup> .K <sup>-1</sup> )	0.12	0.039	Flax: [0.035-0.075] Hemp: [0.040-0.094] Glass wool: [0.04-0.05] Stone wool: [0.035-0.05]	(Kymäläinen and Sjöberg 2008)

## 231 Pith and Bark Microstructures

232 The stem volume constitutes 90% of the sunflower. It is made of two main parts:  
 233 bark and pith. Intuitively, the bark can be expected to be used for applications requiring  
 234 mechanical strength, and the pith for thermal insulation purposes, because of its large  
 235

236 volume fraction of intragranular pores. Preliminary microscopy observations showed that  
 237 the pith and bark both change in appearance along the stem (Fig. 3). The number of  
 238 sclerenchyma fibers in the bark increases going up the stem, while porosity decreases  
 239 from 59% at the bottom to 53% at the top. The pith shows more macroscopic voids at the  
 240 bottom of the stem (63%) than at the top (56%).  
 241



242  
 243  
 244 **Fig. 3.** Main physical and chemical properties of sunflower stems

245  
 246 **Biochemical Composition**

247 Biochemical analysis revealed that the chemical composition did not vary along  
 248 the stem, with a mean composition of 48% cellulose and 14% lignin for the bark, and



249 31.5% cellulose and 2.5% lignin for the pith. Note that the chemical composition of  
250 sunflower stem bark (14% of lignin) is very close to that of jute (13% of lignin)  
251 (Summerscales *et al.* 2010). The chemical composition may directly influence the  
252 material properties of these two parts of the stem. However, it does not completely  
253 explain the variations in material properties observed along the stem. Therefore, the  
254 influence of microstructure along the stem on material properties was examined. Because  
255 it is well known that RH significantly influences the material properties of natural fibers,  
256 hygroscopic tests were performed beforehand.

257

### 258 **Hygroscopic Behavior**

259 The tests results clearly revealed that the diffusion coefficients for moisture of  
260 both the bark and pith specimens were higher at the bottom ( $3.8 \times 10^{-5} \text{mm}^2 \cdot \text{s}^{-1}$  for the bark  
261 and  $200 \times 10^{-5} \text{mm}^2 \cdot \text{s}^{-1}$  for the pith) than at the top of the stem ( $1.4 \times 10^{-5} \text{mm}^2 \cdot \text{s}^{-1}$  for the  
262 bark and  $110 \times 10^{-5} \text{mm}^2 \cdot \text{s}^{-1}$  for the pith). This is primarily because of the difference in  
263 porosity along the stem. The moisture diffusion mechanism depends directly on cell  
264 cavities, as described and explained for other materials such as wood (Times 2002a,b).  
265 Two mechanisms govern the moisture diffusion process in sunflower stems: bound water  
266 diffusion through the cell walls, and vapour diffusion through the cell cavities. Moisture  
267 diffusion through cell cavities is more significant than moisture diffusion through the cell  
268 walls. Therefore, the porosity of both the bark and pith specimens is expected to change  
269 the value of the macroscopic diffusion coefficient obtained from the hygroscopic tests. In  
270 the situation considere in this work, the increase in amount of porosity or decrease in  
271 amount of cell wall content of the specimens is expected to increase the value of the  
272 moisture diffusion coefficient. Subsequently, the effect of various RH levels was  
273 evaluationed relative to both the mechanical and thermal properties.

274

### 275 **Mechanical Properties**

276 Mechanical tests were carried out to evaluate Young's modulus and the strength  
277 of both the bark and the pith. As expected, bark specimens expressed higher Young's  
278 modulus values (4.6 GPa at the bottom and 6.4 GPa at the top) than pith specimens  
279 (0.15 MPa at the bottom and 1 MPa at the top). It is worth noting that high RH tended to  
280 decrease the Young's modulus (a near 10% differential between 0% RH and 75% RH).  
281 However, this effect was less significant than the influence of the sample location along  
282 the stem. The difference in Young's modulus between bark and pith was in accordance  
283 with their chemical composition. Bark has a higher lignin percentage and a lower mean  
284 intergranular pore volume fraction than pith. Furthermore, the Young's modulus of both  
285 bark and pith increased along the stem, obtaining higher values at the top, which was  
286 attributed mainly to the lack of cavities. There was also an increase in the mechanical  
287 strength of bark (from 25 to 31 MPa) and pith (from 3.3 to 23 kPa).

288

289 The Young's modulus of sunflower stem bark (4.6 to 6.4 GPa) is on a par with  
290 other by-product fibers, including oil palm (3.2 GPa) or pineapple fibresones (1.4 GPa)  
291 (Faruk *et al.* 2012). With respect to other natural fibers extracted from stems, such as  
292 flax, hemp or jute, the Young's modulus of sunflower stem bark is slightly lower (lying  
293 between 10 GPa for jute and 80 GPa for flax fiber) (Ahmad *et al.* 2015). The trade-off  
294 between the Young's modulus and the density is also a key-issue in many applications,  
295 for instance, in the automotive industry. In the case of sunflower stem bark, the specific  
296 modulus (ratio of the Young's modulus by the density) is between 13 and 18  $\text{GPa} \cdot \text{m}^3 \cdot \text{Kg}^{-1}$ ,  
1, which is very close to the value of the Young's modulus of jute (Ahmad *et al.* 2015).

297 This value enables designers to consider the sunflower stem bark for producing  
298 components of vehicles to reduce weight and therefore fuel costs as well.  
299

### 300 Thermal Properties

301 The thermal conductivity also were investigated for both the bark and the pith  
302 (Pennec *et al.* 2013). As expected, pith showed a lower mean thermal conductivity (0.039  
303  $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ) than bark (0.12  $\text{W}\cdot\text{mm}^{-1}\cdot\text{K}^{-1}$ ). In contrast to the Young's modulus, the thermal  
304 conductivity of both the bark and the pith did not evolve along the stem. The variation of  
305 the pore volume fraction is thought to be too small to have a significant influence on  
306 thermal conductivity. Moreover, both bark and pith demonstrated significant heat  
307 capacity values (mean values of 1400 and 1300  $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$  for bark and pith, respectively)  
308 approaching levels found in hemp fiber (nearly 1500  $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ ). Additionally,  
309 preliminary experiments carried out while varying the RH of the samples from 0 to 100  
310 wt% revealed that the thermal conductivity of pith and bark can double because of the  
311 absorbed water.

312 In terms of thermal insulation applications, the pith showed interesting thermal  
313 properties. Its thermal conductivity (0.039  $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ) was even better than the thermal  
314 conductivity of glass wool (0.046  $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ) and its heat capacity was on a par with  
315 hemp. The thermal conductivity of the pith was competitive with other natural fibers. For  
316 example, flax's ranges between 0.035 to 0.075  $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ , depending on the harvest  
317 location and the variety (Kymäläinen and Sjöberg 2008). Hemp's is between 0.040 and  
318 0.094  $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  (Kymäläinen and Sjöberg 2008). Therefore, sunflower pith may be  
319 considered as raw materials for thermal insulation applications.  
320

### 321 Ageing Results

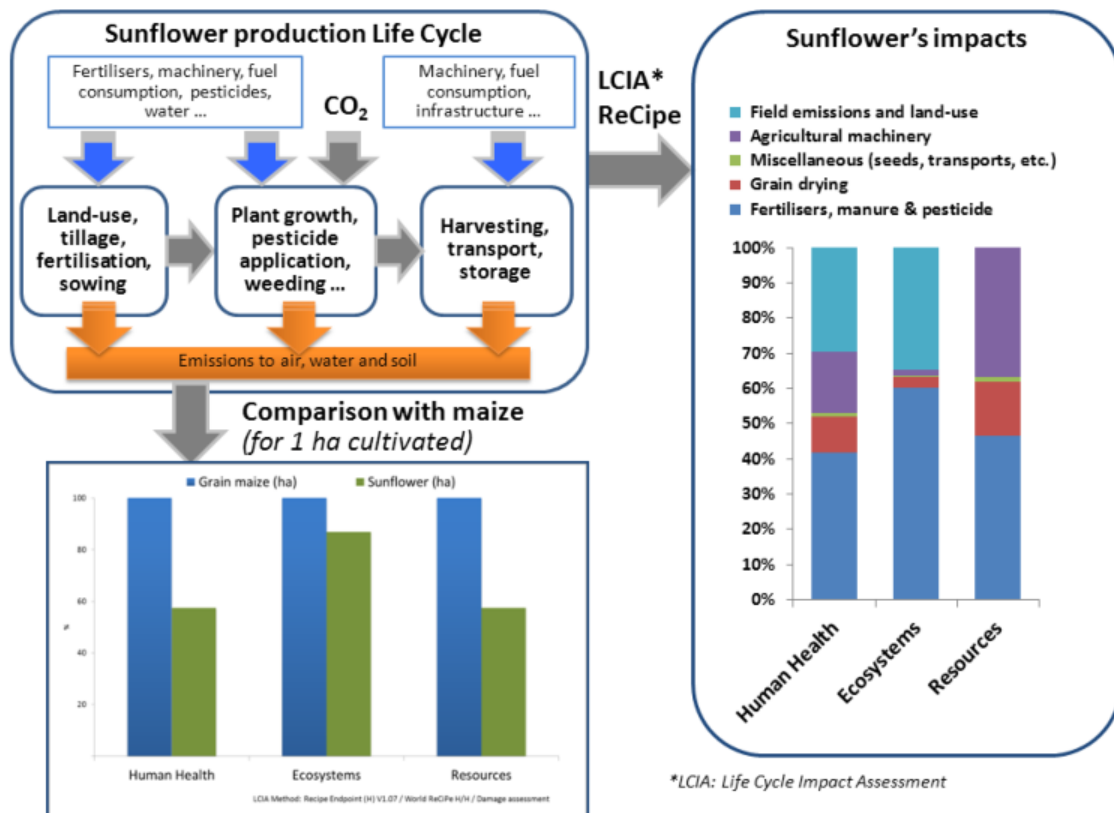
322 The biodegradable character of sunflower plants makes them environmentally  
323 safe for waste disposal but makes sunflower-based fiber sensitive to weather conditions.  
324 The ageing properties were studied by testing the influence of different weather  
325 conditions such as humidity, temperature, and UV radiation on the variation in Young's  
326 modulus. The Young's modulus of both the bark and the pith were unaffected if only one  
327 weather condition was increased (temperature or moisture exposure alone). Increasing  
328 both the temperature and moisture exposures (80 °C and 75% RH) did not affect the  
329 Young's modulus of the bark, but it diminished the Young's modulus of the pith by about  
330 30% after one week (and 50% after two weeks). After UV treatment for 1000 h  
331 (equivalent to a 3-year exposure), the oxidation of organic matter was detected by FTIR  
332 measurements. Absorption bands at 1703 and 3500 to 2200  $\text{cm}^{-1}$  were detected and  
333 attributed to the C=O and OH stretching vibrations of carboxylic groups, respectively.  
334 These carboxylic acids were most likely from the breaking of polymeric chains.  
335

### 336 Environmental Impact

337 Finally, the environmental impact of exploiting sunflower stems in the rural  
338 economy was investigated. Life cycle assessment is a requirement to evaluate the  
339 environmental impacts of natural fibers (Joshi *et al.* 2004). The reasonable quantities of  
340 water, fertilizers, and pesticides that are needed per hectare seem promising compared to  
341 maize, rape, and wheat crops. Using available EcoInvent data for crop production  
342 (Nemecek and Kagi 2007), it is possible to assess the impact of sunflower plants over  
343 their entire life cycle. Figure 4 presents these results using the ReCipe impact assessment  
344 method (Goedkoop *et al.* 2009) for three impact categories, which are human health,

345 ecosystems, and resources. The various effects of sunflower plants over their life cycle  
 346 were compared against those of maize, which is the most widely grown grain crop. The  
 347 question of a partial allocation of the agricultural phase to stems depends on their status.  
 348 As long as sunflower stems are considered agricultural waste, then no impact of the  
 349 agricultural phase should be allocated to their production. However, a huge surge in the  
 350 use of sunflower stems for biocomposite applications would lead to competition for their  
 351 exploitation, which would prompt a change in the status of sunflower stems and a move  
 352 them up from “waste” to a valuable “co-product.” In this case, either (i) the part of the  
 353 environmental impacts of sunflower production should be allocated to the production of  
 354 the stems, based for instance on a financial allocation; or (ii) the system boundaries  
 355 should be extended and substitutions should be studied to share agricultural impacts.

356 Sunflower cultivation has less environmental impact, in terms of water need,  
 357 fertilizer, and pesticide, than a standard crop production such as maize. Moreover, using  
 358 existing by-products constitutes an environmental benefit in comparison with other natural  
 359 fibers, which require a dedicated agricultural field that increases the environmental  
 360 impacts.



361  
 362 **Fig. 4.** Environmental analysis of sunflower production  
 363  
 364

## 365 CONCLUSIONS

366  
 367 In Europe and in the USA, legislative and public opinion pressures affecting the  
 368 use of bio-based materials are rising (Technology Road Map for Plant/Crop Based  
 369 Renewable Resources 2020 in the USA or the Biomass Action Plan in Europe). The

370 sunflower stems, not yet valued, constitute a promising raw material for a variety of  
371 applications. This is mainly due to their mechanical and thermal properties as well as to  
372 their environmental impact. Detailed studies will be required in order to characterize the  
373 influence of different treatments or industrial processes on the properties of the sunflower  
374 bark and pith, depending on the industrial application. Sunflower also offers a number of  
375 socioeconomic assets in a growing natural fiber market of large stocks, low price, and  
376 worldwide crop ability. It is also necessary to study in details (like other natural  
377 resources), such as how to organise the local agricultural sector for collecting and storing  
378 the sunflower stems as well as processes for their conversion into bio-based materials.  
379 Further research is therefore needed for moving away from a promising raw material to  
380 an effective solution in terms of both physical properties and socio-economic  
381 valorization.

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