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1 **Comparison of the properties of flax shives based particleboards prepared using**  
2 **binders of bio-based lignin and partially bio-based epoxy resin**

3

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10

11 **Abstract**

12 In order to reduce formaldehyde emissions, an experimental investigation of lightweight  
13 flax shives based particleboards, prepared using two different binders: bio-based lignin  
14 (lignosulfonate) and partially bio-based epoxy resin (greenpoxy 56), was undertaken. The  
15 flax based particleboards (with a target density of 500 Kg/m<sup>3</sup>), were elaborated by a  
16 thermo-compression process using 20 wt% of binder content. The flax shives were directly  
17 valorised as they had no pre-treatment, in order to qualify their potential as a raw material.  
18 Bending, compression and fire resistance tests showed that the mechanical and flame  
19 performances of lignosulfonate-based particleboards were high compared to those of  
20 greenpoxy56 based panels. Nevertheless, the latter were found to have an interesting  
21 dimensional stability after water immersion and good insulating properties. Moreover, both  
22 lignosulfonate and greenpoxy 56 based particleboards met the minimum EN 15197  
23 requirements for non-load bearing flaxboards for use in dry conditions (Type FB2). Such  
24 results illustrated the competitiveness of the studied particleboards, as bio-sourced  
25 structures, compared to urea-formaldehyde based panels.

26 **Keywords:**

27 Particleboard; Flax shives; Bio-based binders; Mechanical properties; Thermal properties

28

## 29 **1 Introduction**

30

31 Binding agents are widely used in particleboard applications and they create most of the  
32 bonds in a particleboard [1]. Phenol-formaldehyde (PF) resin is a widely used binding  
33 agent, owing to its strength and moisture resistant properties [2,3]. Other resins, such as  
34 urea-formaldehyde (UF), resorcinol-formaldehyde (RF), melamine-formaldehyde (MF)  
35 and diisocyanates are used in particleboards [4,5]. However, these are toxic and  
36 expensive [2,6]. Thus, the demand for the replacement of such adhesives is not only due  
37 to environmental concerns but also out of economic interest [2].

38 Lignin has a role as a binding agent in the biomass itself. Several studies have reported  
39 on the partial replacement of phenol in PF resin by several types of lignin, varying the  
40 proportions and incorporation of lignin with PF or other commercial resins in order to  
41 fabricate particleboards. The partial replacement of phenol in PF resin by organosolv  
42 lignin and modified organosolv lignin (phenolated-lignin) was tested [2]. The chemical  
43 modification of lignin is usually performed to increase the reactive sites and thus, their  
44 reactivity while undergoing condensation reactions. Many studies have been undertaken  
45 on the modification of lignin. Particleboards were produced using resins where  
46 chemically modified lignin (such as methylolated lignin, demethylated lignin and  
47 methylolated black liquor) partially replaced phenol in PF resins [3]. In certain studies,  
48 lignin replaced phenol both partially and completely in phenol-formaldehyde resins in  
49 the fabrication of fibreboards [7].

50 With respect to the incorporation of lignin with conventional resins, modified lignin  
51 (such as hydroxymethylated lignin and glyoxalated lignin) were incorporated as a resin

52 component (diisocyanates and with/without PF resins) in various proportions and used  
53 for the fabrication of particleboards [8]. Lei H. et al. [9] prepared particleboards using  
54 different resin components, such as glyoxalated lignin, glyoxal, tannin, diisocyanates  
55 and PF resins. Stephanou and Pizzi [10] used various proportions of methylolated kraft  
56 lignin, diisocyanates and PF resins as binders for the preparation of particleboards.  
57 Anglès et al. [11] used pre-treated sawdust material for the fabrication of panels with  
58 different types of lignin as the only binder, which varied from 5% to 20% on a dry  
59 solids basis. They also prepared binderless panels and compared the effect of adding  
60 lignin to the panels. Velasquez et al. [12] used kraft lignin at different proportions,  
61 mixed with steam-exploded pulp for the fabrication of particleboards. Privas and  
62 Navardused [13] pre-treated flax fibres for fabrication of panels using liginosulfonate as  
63 the only binder.

64 On the other hand, the use of thermosetting matrices as a binder in fibre-reinforced  
65 composites is increasingly common because of its mechanical performance and  
66 compatibility with different fabricating processes [14,15]. The thermosets have low  
67 viscosity compared to thermoplastics, which permits relatively better impregnation  
68 among the fibres. Epoxy resin is one of the most widely used thermosetting matrices. It  
69 is even used with plant fibres such as flax, hemp, bagasse and sisal [16–20].

70 In recent decades, the development of an alternative matrix to the conventional oil-  
71 based ones has gained interest. The context extends to reducing the CO<sub>2</sub> footprint and  
72 dependence on fossil fuels. Formaldehyde-free bio-sourced phenolic resins and  
73 bisphenol A-free epoxy resins are the outcomes of such an approach [21].

74 Several studies have focused on the use of long flax fibres as a reinforcement in bio-  
75 sourced composites but few have been interested in the valorisation of flax shives,

76 which comprise the woody core generated as a by-product in the flax scutching process.  
77 These shives are not valorised as primary materials but for bio-fuel, animal bedding and  
78 mulch. These plant particles which are widely available in the north-west of France,  
79 have a porous structure and mechanical strength that promises to become a potential  
80 replacement for wood particles in light agglomerated panels.

81 In general, a wide variety of agro-resources such as bagasse [22], hazelnut and almond  
82 husk residues [23], [5] and flax shives [24] have been combined with thermosetting  
83 based formaldehyde. However, there has been little mention of the use of lignosulfonate  
84 or epoxy as being the only binders for the fabrication of plant particleboards [25,26].

85 In this study, GreenPoxy 56 (a partially bio-sourced thermosetting resin, which has up  
86 to 56% of its molecular structure from plant origins) and calcium lignosulfonate are  
87 used as a matrix for particleboards. Furthermore, flax shives, an agricultural residue, are  
88 directly valorised as they were and with no pre-treatment. Hence, the fabricated  
89 particleboard is novel owing to such a combination of the material and the binder.

90 In the present study, because of environmental concerns and local resource  
91 development, a straightforward method for the fabrication of innovative flax shives  
92 based particleboards using the bio-based binder lignosulfonate (PLS) and a  
93 conventional, partially bio-based binder epoxy resin (PER) has been established and  
94 presented. The mechanical and thermal properties of fabricated PLS and PER  
95 particleboards are studied, as well as water absorption, thickness swelling and flame  
96 tests. An attempt to understand the relationship between fabrication, structure and  
97 properties of bio-based particleboards and interactions within them has been  
98 undertaken.

99

100 **2 Material and methods**

101 Flax shives were purchased from Terre de Lin (cooperative engaged in the cultivation  
102 and processing of flax in France). The morphological analysis of the raw flax shives  
103 used in this study was performed by using the optical microscope Keyence VHX-700F.  
104 It was performed from a sample containing about 100 particles. Flax shives exhibit  
105 coarse stick shapes with a 8.3 mm average length, a 1.2 mm average width and a 0.3  
106 mm average thickness. Table 1 summarises the measured geometrical characteristics of  
107 raw flax shives.

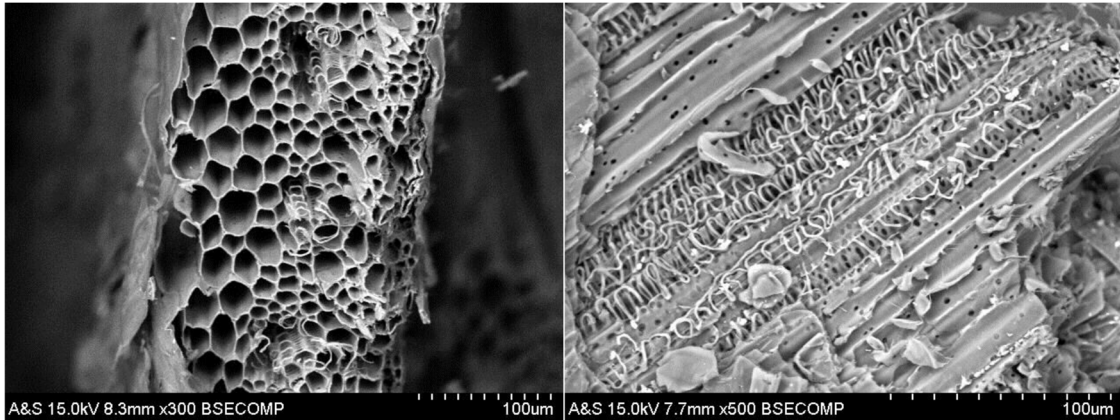
108 **Table 1. Geometrical characteristics of raw flax shives.**

	Length ( $\mu\text{m}$ )	Width ( $\mu\text{m}$ )	Thickness ( $\mu\text{m}$ )
Raw Flax Shives	$8371 \pm 5018$	$1248 \pm 498$	$329 \pm 108$

109

110 The moisture content of these particles prior to particleboard production was about  
111 10.2% wet basis (w.b.). The apparent density of flax shives was approximately equal to  
112  $0.1 \text{ g/cm}^3$ . Such a value is due to the alveolar structure of these particles which  
113 highlights their potential for insulating panels (Fig. 1). The real density of the flax  
114 shives was measured by pycnometer and found to be  $0.149 \text{ g/cm}^3$ .

115



116

117

118

119

120

121

122

123

(a)

(b)

**Fig. 1.** (a) The alveolar structure of flax shives and (b) presence of holes on its walls.

The flax shives used for this study belong to the same batch that was already studied in the laboratory using the Van Soest approach [27]. Table 2 summarises the measured biochemical composition of the biomass.

**Table 2.** Flaxshivesbiochemical composition [27].

<b>Organic matter</b>	<b>Composition</b>
	(%)
<b>Cellulose</b>	43 ±1.3
<b>Hemicelluloses</b>	19.5 ±0.7
<b>Lignin</b>	32.3 ±1.7
<b>Other solubles</b>	5.2 ±0.2

124

125

126

127

128

This study uses flax shives in their raw state, as they are marketed, without any heating or the addition of external wax or water-repellent chemicals.

Commercial partially bio-based epoxy resin GreenPoxy56 (GP 56) and calcium lignosulfonate (LS) were used separately as a binder in the manufacturing of

129 particleboards. GP 56 resin was purchased from Sicomin and crosslinked by SD8822  
130 hardener according to the weight ratio of 100/31, as suggested by Sicomin. The  
131 combination of these two components ensures good fluidity in the mixture compared to  
132 the other tested hardeners, whose dynamic viscosity at 20 ° C is 507 mPa.s. The LS was  
133 provided by Carl Roth GmbH + Co. KG.

134

## 135 **2.1 Fabrication of particleboards**

136 The flax shives were sieved through meshes of 4 mm and 1 mm diameter. The residue  
137 in the 1 mm sieve was used for the fabrication of particleboards. A quantity of LS,  
138 corresponding to 20% relative to the total weight of the panel, was dissolved in water  
139 and then mixed with the flax shives (80% relative to the total mass). The mass of added  
140 water was not included in the total weight due to its evaporation at the time of  
141 manufacture. The resulting mixture was thermo-compressed in a Scamex Presse 15T at  
142 190°C for 30 minutes. Epoxy resin (20% w/w) was mixed with the flax shives (80%  
143 w/w) and thermo-compressed at 90°C for 10 minutes. For all panels, the pressure  
144 applied corresponded to the pressure required to close the piston mould, which  
145 guaranteed a constant volume of the panels 300\*300\*10 mm<sup>3</sup>. For this, steel shims were  
146 placed between the mould and the piston to ensure a similar thickness in all boards.  
147 During the manufacturing cycle, the press was controlled by the gap between the piston  
148 and shims.

149 For all PLS and PER panels, the target density was equal to 500 kg/m<sup>3</sup>. Nevertheless, it  
150 was proved that, after manufacturing under these conditions, PER panels had a mean  
151 density of approximately 470 kg/m<sup>3</sup> lower than that of the PLS ones (500 kg/m<sup>3</sup>). This  
152 amounts to an increase in the thickness of PER of about 10.8 mm due to a spring-back



153 after the removal of the upper plate of the press. In fact, during the hot pressing a large  
154 amount of water vapour migrates towards the centre of the panel, which requires a  
155 longer pressing cycle to allow the evacuation of moisture. The release of pressure when  
156 the moisture content in the core of the panel is higher may provoke spring-back or non-  
157 reversible dimensional changes [28]. Such a density difference (of 30 kg/m<sup>3</sup>) will have  
158 little influence on the mechanical and physical properties of particleboards. However,  
159 thermal properties can be affected. Therefore, for a better comparison between PER and  
160 PLS insulation properties, the thermal results of PER panels were adjusted to 500 kg/m<sup>3</sup>.  
161 Moreover, observations by X-ray micro-tomography were carried out on samples taken  
162 from the PLS and PER panels, in order to determine the porosity rate between the flax  
163 shives. The processing of the images obtained by the Image J software gave a porosity  
164 rate equal to  $8.8 \pm 2.9\%$  for the PLS panels and  $10.1 \pm 5.3\%$  for the PER ones. This  
165 small difference in the porosity rate will allow comparison between the mechanical and  
166 thermal properties of the PLS and PER panels.  
167 The processed particleboards were preserved at room temperature ( $\sim 20^{\circ}\text{C}$ ) and relative  
168 humidity ( $\sim 55\%$ ) until used in the experiments.

169

## 170 **2.2 Mechanical tests**

171 Three-point bending, compressive and internal bond tests were performed on the  
172 particleboards using a type 5867 INSTRON universal testing machine. For each type of  
173 test, at least five specimens were taken from different panels and tested to ensure the  
174 reproducibility of the results. All the mechanical tests were conducted at least one week  
175 after the particleboards had been manufactured under room temperature and humidity.

176 **Three-point bending** tests were performed to study the flexural behaviour of the PLS  
177 and PER particleboards. The modulus of elasticity (MOE) and modulus of rupture  
178 (MOR) were extracted. The tests were conducted on longitudinal specimens according  
179 to Standard NF EN 310.

180 **Compression** tests were carried out on specimens of dimensions 50\*50\*10 mm<sup>3</sup>  
181 according to the ASTM C365 standard.

182 **Internal bonding strength** corresponds to the force required to break the sample by a  
183 z-directional tensile test. It gives an estimation of the shive-to-shive bond. Specimens of  
184 dimensions 50\*50\*10 mm<sup>3</sup> were glued onto stainless steel supports with  
185 SR7100/SD7105, provided by Sicomin. The thickness of the adhesive layer was  
186 approximately 0.5 mm. Then, samples were tested according to the NF EN 319  
187 standard.

188

### 189 **2.3 Thermal conductivity**

190 A Netzsch HFM 436 Lambda meter was used to measure the thermal conductivity  $\lambda$   
191 (W/m.K) of the particleboards. Two panels of dimensions 300\*300\*10 mm<sup>3</sup> were  
192 perfectly superimposed to correctly establish the balance between the upper plate (hot)  
193 and the lower plate (cold) set at different temperatures, where the heat flows from the  
194 upper towards the lower plate. The temperature gradient ( $\Delta T$ ), which is the difference  
195 between the upper and lower plates, was 20°C.

196

### 197 **2.4 Water absorption and thickness swelling**

198 The water absorbed (WA) and the thickness swelling (TS) of the processed  
199 particleboards were measured by immersing them in water at room temperature for 24

200 hours. Sampling was carried out by cutting the processed particleboards into specimens  
201 of 50\*50 mm<sup>2</sup>. The weight of the specimen and thickness at the centre were measured  
202 prior to their immersion in water and after removal.

203

## 204 **2.5 Flame test**

205 “The particleboards’ fire resistance was tested according to the NF EN ISO 11925-2  
206 Standard. The measurements were undertaken in a dedicated chamber where samples of  
207 dimensions 290\*90\*10 mm<sup>3</sup> were exposed to a propane flame, inclined by 45° on the  
208 lower edge of the sample, for a duration of 15 s. Experiments were carried out in  
209 triplicate on each board. After exposure to the flame, the absence of ignition and of  
210 flaming droplets was controlled and the height of the damaged zone was measured  
211 [27]”.

212

## 213 **3 Results and discussion**

### 214 **3.1 Mechanical properties**

215 According to standard ANSI A208.1 (1999), particleboards have been classified into  
216 three types of nominal density: low (<640 kg/m<sup>3</sup>), medium (640-800 kg/m<sup>3</sup>) and high  
217 (>800 kg/m<sup>3</sup>). In this study, the density of PLS and PER particleboards was about 500  
218 kg/m<sup>3</sup>. The choice of this low density was made so that our panels could be compared  
219 with other less dense materials, such as balsa and cork.

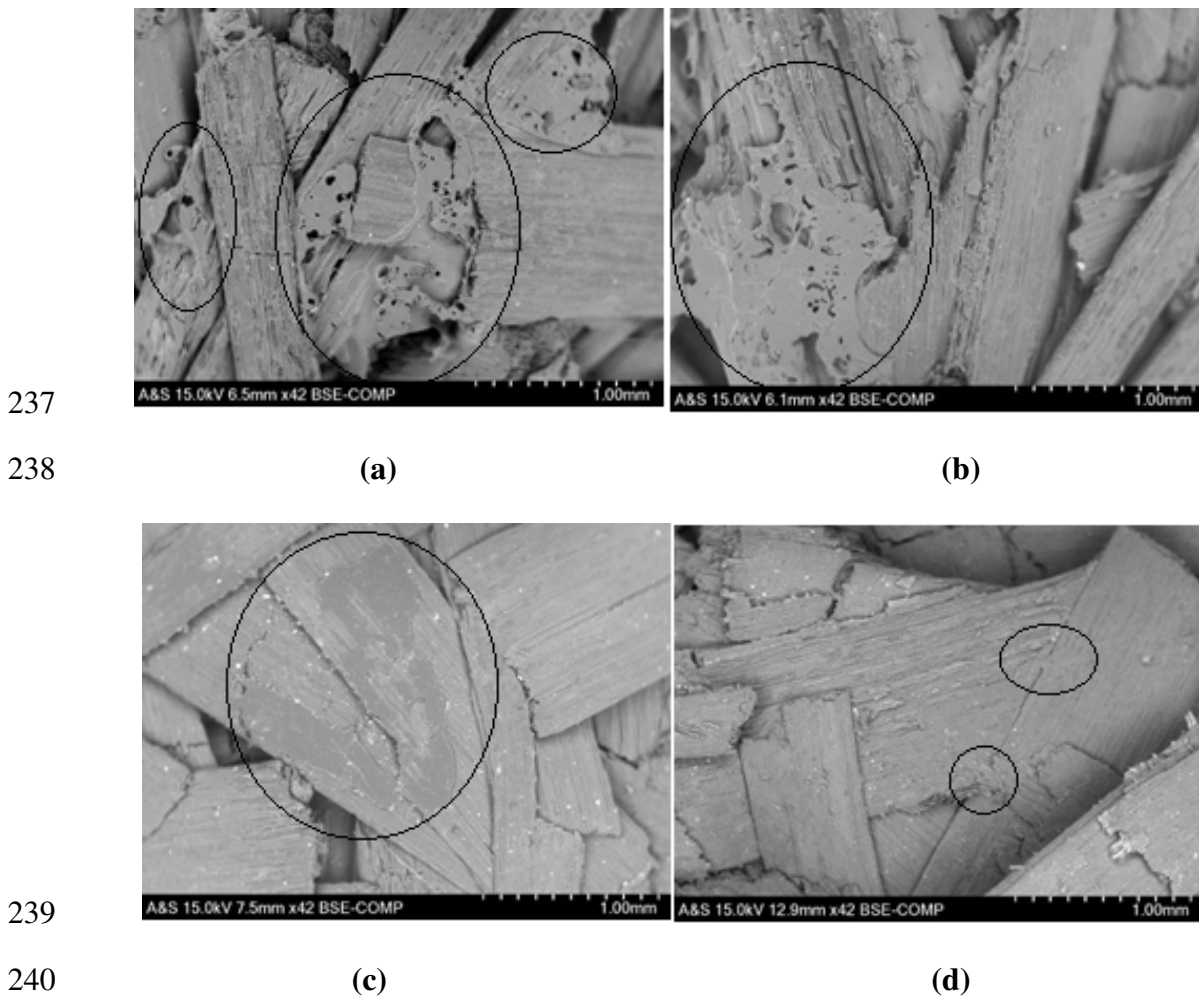
220 Table 3 summarises the mean values and standard deviations of the mechanical  
221 properties for both PLS and PER particleboards under bending, compression and  
222 internal bond investigation, compared to values given by standard EN 15197 (2007) for  
223 non-load bearing flaxboard in dry conditions (Type FB2).

224 **Table 3.** Mechanical properties of PLS and PER thermo-compressed particleboards  
 225 and requirements from NF EN 15197 standard of FB2 type panels.

	PLS	PER	FB2
<b>Density</b> (kg/m <sup>3</sup> )	497.6±4	469.9±18	-
<b>MOE</b> (MPa)	2467±202	1517±225	1500
<b>MOR</b> (MPa)	9.9±1.2	8.4±1.2	9
<b>E<sub>comp</sub></b> (MPa)	79.3±2.6	58.3±4.3	-
<b>σ<sub>10</sub></b> (MPa)	5.4±0.16	3.6±0.27	-
<b>IB</b> (MPa)	0.17±0.01	0.41±0.03	0.23

226  
 227 The results show that the MOE (2467.0 MPa) and MOR (9.9 MPa) values of PLS  
 228 particleboards are higher than those of the PER ones (1517.0 MPa and 8.4 MPa,  
 229 respectively). Moreover, the standard deviation is less in the PLS particleboards.  
 230 Essentially, this reveals a better wetting of flax shives by the lignosulfonate solution,  
 231 leading to improved bonding. In fact, the optimum amount of solution used for the  
 232 manufacture of PLS boards, results in a homogenous mixing of the flax shives and the

233 lignosulfonate. The amount of time spent in the thermo-compression press allows the  
234 evaporation of the water and plasticisation of the lignosulfonate under temperature and  
235 pressure. This could lead to a consistent mechanical strength for the PLS particleboards.  
236



241 **Fig. 2.** SEM images of the thermo-compressed PLS (a, b) and PER (c, d) with  
242 highlight over the areas with matrix.

243 However, the relatively viscous and lower volume epoxy resin used does not result in  
244 such a level of homogeneity in the mix. Thus, the matrix distribution is more  
245 heterogeneous. This can be seen on the SEM images. Fig. 2a and Fig. 2b show several

246 binder bridges that connect the flax shives. In contrast, Fig. 2c and Fig. 2d show less  
247 abundant and continuous resin bridges.

248 Considering the literature, lignosulfonate binder constitutes a veritable internal adhesive  
249 agent that provides better cohesion inside the particleboards. Nguyen et al. [25] showed  
250 that replacing a part of the nerve or bone glue with 9% (w/w) of lignosulfonate  
251 considerably increases both the modulus and bending strengths of bamboo  
252 particleboards. Anglès et al. [11] showed that the addition of lignin (up to 20%)  
253 significantly increases the mechanical properties of softwood panels compared to  
254 binderless ones. Evon et al. [29] showed that because of the highest link between  
255 cellulosic chains and lignins inside raw shives, the mobilisation of the ligneous binder  
256 during the thermo-pressing process seemed to be really difficult. Thus, the particle  
257 wetting and panel cohesion are insufficient. Adding 25% Biolignin improved the  
258 wettability of the surface area of the particles. As a result, the adhesive properties of this  
259 natural binder activates cross-linking formation between the cellulosic chains in plant  
260 particles and bending properties are improved.

261 Furthermore, it can be observed that flax shives have interesting mechanical properties  
262 compared to other particles used in binderless particleboards, such as sun flower [27],  
263 banana trunk waste [30] and bark and leaves of oil palm biomass [31]. This can be  
264 attributed to the high percentage of cellulose chains (43%) and lignin (32.3%) in flax  
265 shives, which are the main structural components providing strength and stability.

266 According to standard EN 15197, the bending properties of PLS particleboards under  
267 investigation satisfy the requirements for non-load bearing flaxboard for use in dry  
268 conditions (Type FB2). However, the MOR of PER boards ( $8.4 \pm 1.2$  MPa) is slightly  
269 below the standard value (9.0 MPa).

270 Beyond the bending response, the PLS panels showed an even performance in  
271 compression with a modulus and compressive stress at 10% relative deformation,  
272 respectively (equal to 79.3 MPa and 5.4MPa vs 58.3 MPa and 3.6 MPa for PER  
273 particles). These low compressive properties of PER panels were attributed to its high  
274 porosity rate, which reduces its compactness. Such results reaffirm interest in the use of  
275 PER particleboards as an insulator material in construction.

276 However, the internal bonding strength of PLS particleboards (0.17 MPa) seemed very  
277 low compared to PER ones (0.41 MPa). This reveals that the mechanical properties of  
278 the bio-based epoxy resin, which are very high compared to bio-based lignin, strengthen  
279 and increase the internal bonds of PER particleboards.

280

### 281 **3.2 Thermal conductivity**

282 As explained above, for a better comparison between PER and PLS insulation  
283 properties, thermal results were adjusted to 500 kg/m<sup>3</sup>.The results reveal that PER  
284 particleboards are more thermally insulating than PLS ones, presenting a mean value of  
285 thermal conductivity equal to  $0.074 \pm 0.002$ W/m K as opposed to  $0.081 \pm 0.001$  W/mK  
286 for PLS (see Table 4).

287 Several parameters directly affect thermal conductivity, such as the nominal density, the  
288 manufacturing conditions (pressure and temperature) and the raw material utilised in the  
289 production of the particleboard [32].

290

291 **Table 4.** Raw particles and particleboards thermal conductivity. Density of  
292 particleboards is 500 kg/m<sup>3</sup>.

293 \*The real density of Cement-flax shives particleboard FSC was 520 kg/m<sup>3</sup>. But, it was  
 294 adjusted to 500 kg/m<sup>3</sup>.

<b>Materials</b>	<b>Thermal conductivity (W/m.K)</b>	<b>References</b>
<b>FS bark</b>	0.042±0.001	
<b>SF bark</b>	0.051±0.002	
<b>FS binderless</b>	0.077±0.001	[27]
<b>SF binderless</b>	0.077±0.002	
<b>FUF</b>	0.074±0.002	
<b>SUF</b>	0.075±0.001	
<b>FSC*</b>	0.118±0.005	[33]
<b>PER</b>	0.074±0.002	Present study
<b>PLS</b>	0.081±0.001	

295  
 296 In this study, the dimensions and density of the panels and the nature and quantity of the  
 297 flax shives used are identical. Thus, the difference in thermal conductivity hints at the  
 298 binder and the porosity of the particleboard. The porosity lies within the individual flax  
 299 shives due to its alveolar structure (Fig. 1) and between shives.  
 300 The addition of a binder consumes such cavities. However, as already explained in the  
 301 section on mechanical properties, the distribution of the bio-based epoxy is more  
 302 heterogeneous. So, porosity distribution in PER should explain the difference in thermal  
 303 conductivity compared to PLS.  
 304 Cravo et al. [34] explained the effect of the high porosity in particleboards on the  
 305 reduction of thermal conductivity. In fact, few solid contacts result in many voids being



306 filled with air. The heat transfer in the panels occurs through the solid particles and the  
307 air. The latter has lower thermal conductivity than the particles. As a result, the  
308 insulation of the particleboards increases.

309 Regardless of the porosity rate, comparing the thermal conductivity of the binderless  
310 flax shives panels (0.077 W/m.K) with those of PER and FUF (0.074 W/m.K), PLS  
311 (0.081 W/m.K) and FSC (0.118 W/m.K), seem to show that the thermoset resin  
312 (GreenPoxy 56 and urea formaldehyde) have improved the thermal insulation of the  
313 panels contrarily to the bio binder and cement. Looking at the literature, it seems that  
314 epoxy cross-linked polymers are good thermal insulating materials [35], [36].

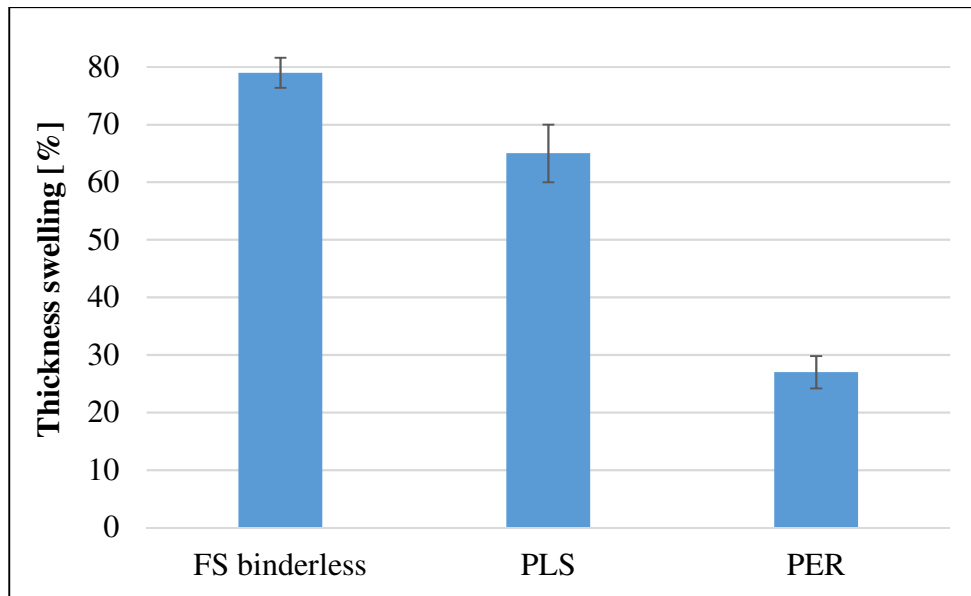
315 According to Wang [37], materials with thermal conductivities lower than 0.25 W/m.K  
316 are considered to be thermal insulators. Therefore, despite the scattering of the thermal  
317 conductivity results in this study and in the literature, plant particleboards have been  
318 shown to have insulating properties, which are required in building applications thanks  
319 to their alveolar structure and important internal porosity.

320

### 321 **3.3 Dimensional properties**

322 Fig. 3 and Fig. 4 present the results of thickness swelling (TS) and water absorption  
323 (WA) of PLS and PER particleboards after immersion in water for 24h, respectively as  
324 well as previously measured results for bulk flax shives and flax shives (FS) binderless  
325 boards [27]. It has been shown that TS results for FS binderless board ( $79\pm 2.6\%$ ) are  
326 higher than those of PLS panels ( $65\pm 5\%$ ), which, in turn, are more than two times  
327 higher than PER ones ( $27\pm 2.8\%$ ). Likewise, the WA of FS binderless panels  
328 ( $250\pm 4.5\%$ ), which is directly related to TS, is higher compared to those of PLS

329 (176±8%) and PER (133.46±11%) boards. Bulk flax shives scored the highest WA  
330 value (295±8%).



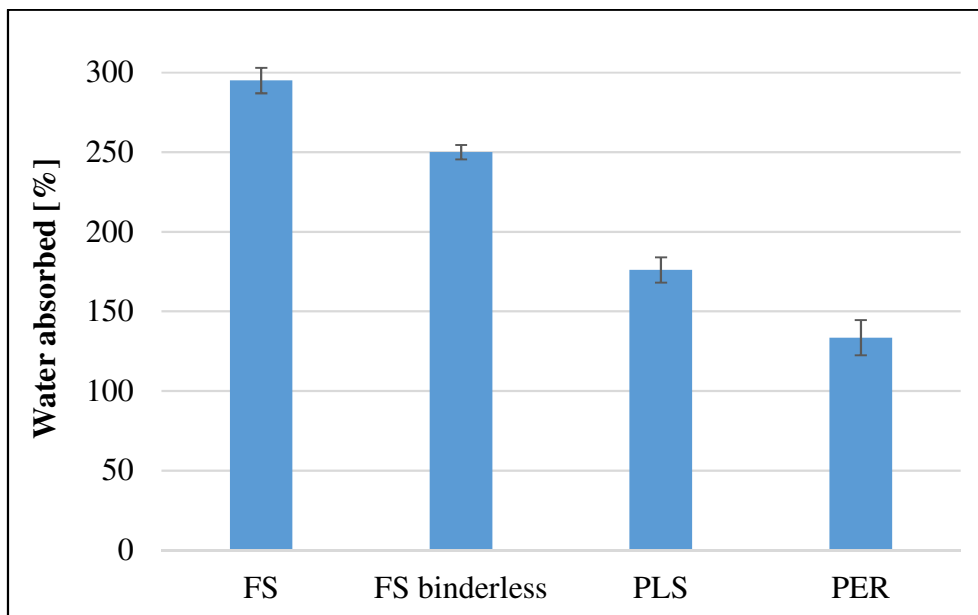
331

332

**Fig. 3.** Thickness swelling of specimens cut out from flax shives binderless  
333 particleboards (FS), PLS and PER.

333

334



335

336

**Fig. 4.** Water absorbed of bulk flax shives (FS) and specimens cut out from FS  
337 binderless particleboards, PLS and PER.

337

338

339 Compared to other plant particles, such as wood, sunflower, tomato stalks and bagasse  
340 [38], [27], flax shives have the highest TS and WA capacity. This can be explained by  
341 its high alveolar system, thin pore walls, low bulk density and chemical composition.

342 The low water resistance of both FS binderless and PLS particleboards (compared to  
343 PER) can be explained by the higher susceptibility of the bio-glue to hydrolysis in water  
344 than cured GP56 resin networks. During immersion of the bio-based epoxy resin, water  
345 interacts with the polar groups of the resin, conducting the rupture of the hydrogen  
346 bonded interchains and intrachains [39]. However, the diffusing water creates hydrogen  
347 bonds with the flax shives. Therefore, immersion in water reduces but does not  
348 eliminate the interactions between shives and resin and causes the thickness swelling.

349 Therefore, many authors have proposed some treatments and studied their effects on the  
350 water intake of lignocellulosic aggregates. Coating plant particles with hydrophobic  
351 substances (such as linseed oil and paraffin wax) prior to their mixing with resin, is a  
352 commonly used treatment because of its low consumption of energy and friendliness to  
353 the environment [40], [41]. Surface treatment is a further solution to improve the water  
354 resistance. Sain et al. [42] suggest a chemical modification of flax shives in the refiner  
355 in situ by introducing a reaction product of polyols and organic anhydrides. These  
356 different treatments enhance bonding between the hydrophilic particles and  
357 hydrophobic binder and, thus, reduce the affinity to water absorption.

358

### 359 **3.4 Resistance of particleboards to fire**

360 The appearance of the PLS and PER particleboards after fire testing is shown in Fig. 5.

361 The conformity of the panels to the standards is controlled through the measurement of  
362 the height damaged by the flame.



363

364

(a) (b) (c)

365 **Fig. 5.** (a) Aspect after test fire of the whole PLS particleboards, (b) the first PER panel  
366 and (c) the second PER board.

367

368 As soon as a small flame of 2 cm was applied for 15 seconds on the lower edge of the  
369 first PER sample, a smouldering fire developed, which continued even after the burner  
370 was stopped. In parallel, smoke was released. The fire spread inside the panel and the  
371 probes fell down. After 1 minute, the fire was extinguished in the first PER panel. The  
372 damaged height was approximately 13 cm.

373 For the second PER sample, the flames quickly rose up and even exceeded the height of  
374 the panel. The extinction of the flame was not natural. The panel was blackened on all  
375 sides. However, PLS specimens retained their integrity during and after the fire tests on  
376 all four of the samples tested. There was no production of flaming droplets during  
377 exposure to the flames. Moreover, PLS panels showed self-extinguishing behaviour

378 after the burner stopped. The measured height of the damaged zone was equal to  
379  $5.6\pm 0.2$  cm.

380 According to the NF EN ISO 11925-2 requirements on the height limit of the damaged  
381 zone which is acceptable in the building sector (which must not exceed 15 cm) and from  
382 the scattered findings on PER specimens, only PLS panels comply with this standard,  
383 especially with class E.

384 The poor resistance to fire of PER particleboards is essentially caused by the resin,  
385 which is easily flammable. Therefore, several approaches have been conducted in order  
386 to improve the fire resistance of biocomposites, such as chemical modification of  
387 existing adhesives [43], direct addition of flame retardant materials [44], incorporation  
388 of mineral particles into the board composition [45] and surface treatment of  
389 lignocellulosic particles [46].

390

#### 391 **4 Conclusions**

392

393 On the one hand, this study set out to valorise flax shives as an abundant natural  
394 resource in France and, on the other, to investigate the use of alternative binders to the  
395 usual commercial ones based on formaldehyde, in order to produce lightweight  
396 particleboards. Two different binders were separately used: a commercial, partially bio-  
397 based epoxy resin (GP 56) and calcium lignosulfonate (LS).

398 A comparison between the bending and compressive behaviours of LS and GP56 based  
399 particleboards shows that totally bio-sourced panels have better properties than partially  
400 bio-sourced ones due to a better wetting of flax shives by the LS binder. However, this  
401 type of binder influences the dimensional instability of flax based particleboards by

402 increasing their rate of water absorption and thickness swelling. This can be explained  
403 by the higher susceptibility of bio-glue to hydrolysis in water than cured bio-based  
404 epoxy resin networks. Moreover, thermal tests have justified interest in the use of the  
405 bio-based epoxy based particleboards as insulator materials in the building sector.  
406 Nevertheless, the use of these materials in such a field remains critical because of its  
407 poor fire resistance compared to PLS particleboards, which comply with class E.

408

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413

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