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Cement-Bonded Particleboards with Banana Pseudostem Waste: Physical Performance and Bio-Susceptibility

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Abstract: This article evaluates the relevant properties of cement-bonded particleboards (CBPB) made with a portion of maritime pine (*Pinus pinaster*) particles replaced with an agricultural waste, banana pseudostem (*Musa* sp.). The industrial production of CBPB was simulated in the laboratory based on a reference composition defined by a manufacturing company. Test specimens were produced assuming 0%, 25%, 50% and 75% partial replacement of wood particles with banana pseudostem fibres. Some physical properties (bulk density, thermal conductivity, and dimensional stability) and the mould susceptibility of the different variables were assessed. Results show that the thermal conductivity of the boards increased with the banana fibre proportion and ranged between 0.233 W/(m.K) and 0.279 W/(m.K). The bulk density values generally increased with the banana fibre proportion and ranged between 1754–1995 kg/m^3, being the highest value obtained for B50 (equal weight proportion of wood particles and banana fibres). Specimens with a higher percentage of banana fibres have reduced thickness resulting from swelling, ranging between 0.38% and 0.11% (for 0% and 75% of banana fibres, respectively). CBPBs with unsanded surfaces seem to be unsusceptible to mould development, whereas those with sanded surfaces, simulating wearing, show some bio-susceptibility. Mould development increases with the proportion of banana fibre. The results highlight the need for regular maintenance of the particleboards, thus avoiding surface wear over time and resulting in the exposure of the wood particles and/or banana fibres to the outside environment.

Keywords: bio-wastes; banana pseudostem fibres; maritime pine particles; physical properties; mould susceptibility.

1. Introduction

Cement-bonded particleboards (CBPB) are construction materials that are being largely used both in new construction and for the rehabilitation/retrofitting of existing buildings. This article is focused on the durability and degradability of coating materials applied in buildings, namely, to assess the relevant properties of innovative CBPB when raw wood particles were partially replaced with banana tree wastes.

Recently, renewed attention has been given to the use of cement-bonded particleboards (CBPB), particularly with added lignocellulosic wastes [1–5] or alternative wood species [6,7] for numerous applications, such as interior walls, external cladding surfaces, ceiling panels or decorative applications [8,9]. However, it is important to ensure that this replacement does not increase in-service problems and that the in situ behavior is validated.

The conventional composite boards are made of a mixture of wood particles (approximately 23%), typically from waste wood and Portland cement (approximately 62%), additives (e.g., pigments and hardeners, approximately 4.5%), and water (approximately 10.5%) [10]. The use of cement in CBPB gives the final product good fire performance and biological resistance, whereas the use of wood-based products favors the thermal and acoustic insulation properties [11,12]. The compatibility between the two materials depends on several characteristics like wood species, production process, and chemical characteristics [13,14]. One important element to be considered is the polysaccharides (sugar content) that can inhibit cement setting time, thus contributing to lower bonding of wood with cement [4,15]. Nevertheless, this problem can be overcome by using chemical accelerators such as calcium chloride, which will decrease the hydration time of the boards, thus increasing compatibility between the wood and cement [16].

Over the last decades, several studies have been focused on the possibility of using residues of vegetal origin as building composites [17–20]. This practice contributes both to the manufacture of products with lower embodied energy and to the circular economy in the construction sector. Considering the environmental problems caused by the disposal of some biowastes [21,22], incorporating lignocellulosic residues in CBPB composition can be an efficient solution to limit this issue [23]. For example, Rocha Almeida et al. [24] analyzed the possibility of producing CBPB by adding coconut shells from babaçu (*Orbignya* sp.), a palm tree from Brazil, demonstrating that this natural material could improve the mechanical resistance and dimensional stability of the boards. Cabral et al. [25] considered the production of CBPB using Jerusalem artichoke (*Helianthus tuberosus*) stalk particles and found lower values of thickness swelling and water absorption of the boards when compared to those values reported in the literature. Rana et al. [4] studied the effects of the addition of chemical additives and magnesium chloride on the setting time of jute stick CBPB and concluded that the additives can help with the improvement of the physical and mechanical properties of the boards. Cavdar et al. [26] concluded that paper-mill sludge can be used in CBPB formulation, up to 20% of total composite weight, depending on the type of sludge used (grey, black, or a mixture of grey and black). Nazerian and Sadeghiipanah [27] investigated the hydration behavior and physical properties of CBPB by incorporating wheat straw and poplar wood at various ratios. They concluded that, compared with control samples, both the hydration time and compressive strength significantly decline along with increases in lignocellulosic materials quantity. Ferrandez-Villena et al. [3] considered the production of CBPB with Canary Islands palm (*Phoenix canariensis* Ch.) trunks and obtained a low thermal conductivity for the boards (0.054 $W.m^{-1}.K^{-1}$), as well as a good mechanical performance. In parallel, Omoniyi and Olorunnisola [28] examined the effects of methods of manufacture, fiber contents and pretreatment on the physico-mechanical properties of bagasse-reinforced cement composites and concluded that the interaction of these variables had significant effects on the sorption and the strength properties of the composites.

Finally, Ogunsile et al. [29] and Nadhari et al. [30] evaluated the influence of the addition of banana stalk particles (*Musa* sp.) on the physical properties and dimensional stability of CBPB. Ogunsile et al. [29] demonstrated that both thickness swelling and water absorption can increase with higher fibre content, whereas Nadhari et al. [30] found that CBPB specimens formulated with banana stalk treated at 121 °C obtained higher values of thickness swelling and water absorption in comparison with those formulated with stalk with no pre-treatment and treated at 111 °C or 131 °C. However, Nadhari et al. [30] assumed the same banana fibre content for all tested boards, and the study of Ogunsile et al. [29] does not refer the percentage of banana stalk fibres replacing wood particles for each CBPB formulation. Moreover, the biological susceptibility of the boards was not considered by the authors.

Banana plants (*Musa* sp.) are native to Asia but grow in many different environments. They are adaptable to mixed farming and are grown in large areas in tropical and subtropical areas [31]. Its production takes place mainly in Asia (56%), Latin America (26%)

and Africa (15%) [32]. According to FAO [33], it is the main crop in the world, with rising production of 60 million tons in 2000-2002 to 116 million tons in 2017-2019. The production cycle lasts only two years leading to a high volume of waste materials derived from this crop [34,35]. Therefore, the volume of waste produced can be reused for the development of CBPB and other building products.

Focused on the objective of the circular economy, this article studies the viability of producing CBPB with increasing proportions of maritime pine (*Pinus pinaster*) particles replaced with an agricultural waste, banana pseudostem. The industrial production of CBPB was simulated in the laboratory and based on a reference composition defined by a CBPB manufacturing company. Test specimens were produced by replacing wood particles with banana pseudostem fibers in different percentages: 0%, 25%, 50%, and 75%. Some physical properties and the bio-susceptibility of the different specimens were assessed with the aim of determining the influence of the biowaste on panels' features. Considering the good thermal insulation properties of many natural fibers, the insulation capacity of the specimens was studied by analyzing their thermal conductivity and loose bulk density. An additional objective of the present study was to evaluate the immediate (unsanded surfaces, replicating new boards) and long-term (sanded surfaces, replicating weathered boards) mould susceptibility of the boards, as well as their dimensional stability. Ultimately, this work aims at evaluating the feasibility of producing these new boards, thus contributing to the reduction of waste to manage.

2. Materials and Methods

2.1. Materials

2.1.1. Banana Pseudostem Waste

Banana (*Musa* sp.) pseudostem waste was collected from Ribeira Brava municipality, on Madeira Island, Portugal, and first dried in open air. Then, the fibres were manually cut until reaching dimensions of a few centimeters and later, was milled in a laminar mill to reduce the particle size to dimensions of less than 10 mm. The particle size distribution of banana fibres (Figure 1) had been determined previously [36]. Loose bulk density was measured according to EN 1097-3 (1998) [37], both for particles above 10 mm and for the ones below 10 mm. The results are 70 g/m^3 and 130 g/m^3, respectively.

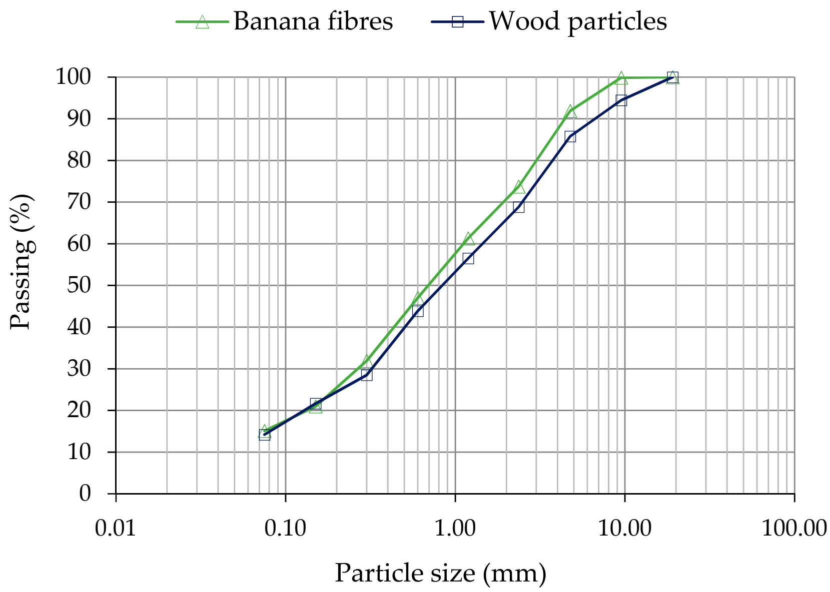


Figure 1. Particle size distribution of the banana fibres and the wood particles (adapted from [36]).

2.1.2. Maritime Pine Particles

Maritime pine particles were provided by the CBPB manufacturing company. Figure 1 shows the particle size distribution of pine particles. Loose bulk density was measured according to EN 1097-3 (1998) [37]. Particles above 10 mm had a measured density of 70 g/m^3, while for particles below 10 mm, the measured density was 150 g/m^3.

2.1.3. Binder and Additives

Portland cement type II (CEM II AL-L 42.5R) was used as a binder, according to a conventional composition [10]. Aluminium sulphate ($Al_2(SO_4)_3$) and sodium silicate (Na_2SiO_3) were both used as additives to improve the compatibility among wood, cement, and water and to reduce setting time [4,38].

2.1.4. Board Manufacturing

CBPBs were produced assuming 0%, 25%, 50% and 75% (by weight) partial replacement of wood particles with banana pseudostem fibres (Table 1). First, dried wood particles and banana fibres were uniformly mixed following the defined proportions in different containers for each composition. The wood particles+banana fibres:cement:water weight ratio was defined and maintained, as well as the percentage by weight of cement (approximately 62%) and a mixed solution of aluminium sulphate and sodium silicate. Thus, the only difference between the samples was the percentage of wood and banana fibres. The mixture was then blended for 3 min a homogeneous material was obtained (Figure 2a). After that, the material was placed into the moulding form (Figure 2b). Care was taken to ensure that the external surfaces of the board samples were produced with finer material, while the interior thickness had an increased content of coarse fibres. As shown in previous studies [39,40], particle-size distribution has a strong influence on the physical and mechanical properties of the boards. It is known that larger particles in the central core (lower density) ensure the better compaction of the boards and improve their mechanical properties. In turn, smaller particles (higher density) in the external layers improve the surface quality and bending properties of the boards [39,40]. Subsequently, the moulds were removed, and samples pressed at 24 MPa for 10 h (Figure 2c) in an oven (50 °C, 50% RH).

Table 1. Mix percentages of the boards (by weight).

Samples	Banana Fibres [%]	Wood Particles [%]
B0	0	100
B25	25	75
B50	50	50
B75	75	25

(**a**) (**b**) (**c**)

Figure 2. CBPB manufacturing: (**a**) homogeneous material obtained after 3 min of blending; (**b**) material placed into the molding; (**c**) layers of material before being pressed at 24 MPa.

Four boards (B0, B25, B50, B75) of 300 mm × 300 mm, with an approximate thickness of 13 mm, were produced, demoulded, and conditioned in a climatic chamber at 23 °C and 45% RH for 7 days. The bulk density of the panels was not controlled during the board manufacturing and was later determined by the ratio between the mass and the volume of the boards (EN 323, 1993 [41]), as reported in Section 2.2. Finally, boards were placed into an oven for 10 h with 70 °C and 45% RH for complete drying.

2.2. Methods

All tests were performed after 10 h of drying at 70 °C and 45% relative humidity (RH) for mass stabilization (Section 2.1.4), and after the board samples were cut for several specimens, based on the specimen dimensions required for each test, defined by CBPB test standards. Table 2 summarizes the tests performed, as well as the sampling and respective dimensions.

Table 2. Tests performed, sampling, dimensions and standards followed.

Properties		Specimens	Area of the Specimen [mm^2]	Standards
Physical properties	Thermal conductivity	3 specimens (1 measurements per specimen) × 4 compositions (B0, B25, B50, B75)	50 × 50	EN 12664 (2001) [42]
	Bulk density	4 specimens × 4 compositions	50 × 50	EN 323 (1993) [41]
	Dimensional stability (water immersion)	4 specimens × 4 compositions	50 × 50	EN 317 (1993) [43]
Biological susceptibility to moulds		3 specimens × 4 compositions × 2 conditions (sanded (p); unsanded (u))	45 × 45	ASTM D5590-17 (2017) [44] and ASTM C1338-19 (2019) [45]

Thermal conductivity measurements, using a heat transfer analyzer ISOMET 2014 and a 60 mm diameter contact probe API 210416, with a measurement range of 0.03–0.6 W/(m.K), were performed for each composition. The test was performed in laboratory equilibrium conditions (T = 23 °C, 45% RH), and thermal conductivity was measured in three specimens of each composition (1 measurement per specimen).

The bulk density of each specimen was determined by the ratio between the mass and the volume of the specimen, based on EN 323 (1993) [41].

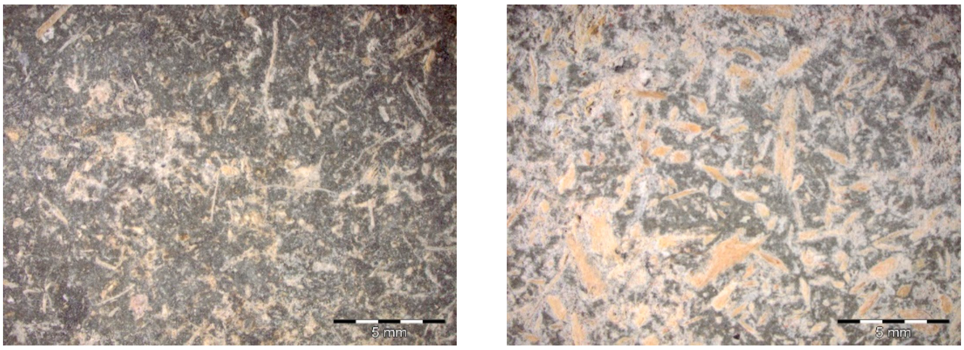
The dimensional stability of each specimen was determined by measuring the thickness swelling. Specimens of each composition cut from the original CBPB were completely immersed in water at a temperature of 20 ± 1 °C for 24 h (EN 317 (1993) [43]). Thickness swelling was obtained using Equation (1).

$$\text{Thickness swelling } (\%) = \frac{(T_2 - T_1)}{T_1} \times 100, \quad (1)$$

In the above equation, T_1 (mm) is the initial average thickness and T_2 (mm) is the final average thickness after water immersion for 24 h.

A method adapted from ASTM D5590-17 (2017) [44] and ASTM C1338-19 (2019) [45], previously described by Parracha et al. [46], was used to evaluate the biological susceptibility of the CBPB to moulds. Six specimens of each composition (B0, B25, B50, B75) were tested considering two different conditions: sanded and unsanded surfaces (Table 2). The surface of half of the specimens (B0p, B25p, B50p, B75p) was sanded twice with Dexter Wood GR120 sanding paper (Figure 3b) removing less than 1 mm of the surface, just enough to expose wood or banana particles. The objective was to simulate some deterioration of the surface layer caused by aging or other events (e.g., human action), thus exposing the wood/banana particles and possibly influencing the biological susceptibility results.

The other three specimens were tested with unsanded surfaces (B0u, B25u, B50u, B75u) (Figure 3a), simulating new boards.



(**a**) (**b**)

Figure 3. Examples of CBPB test specimens before fungal exposure (**a**) B50u unsanded; (**b**) B50p sanded.

Specimens were inoculated with a mixed spore suspension of *Aspergillus niger* and *Penicillium funicullosum* that were selected as representative biodeterioration agents. All specimens were steam-sterilized for 20 min in an autoclave and placed on test flasks previously prepared with culture media (4% malt, 2% agar). Afterwards, 2 mL of spore suspension was uniformly applied on the specimens' surface and culture media, and then the flasks were incubated for four weeks in a culturing chamber (T = 22 ± 1 °C, 70 ± 5% RH).

Three control specimens of maritime pine with similar dimensions were used to verify the viability of the fungal strains, thus allowing the validation of the test. All of the specimens (CBPB and controls) were visually assessed each week following the scale defined in Table 3. At the end of the four-week testing period, specimens were removed from the flasks, and the percentage of the contaminated surface was evaluated using a stereo microscope Olympus B061.

Table 3. Rate of mould growth (ASTM D 5590-17, 2017) [43].

Rating	Description	Contaminated Surface [%]
0	None	0
1	Traces of growth	<10
2	Light growth	10 to 30
3	Moderate growth	30 to 60
4	Heavy growth	>60

3. Results and Discussion

3.1. Thermal Conductivity

Figure 4 presents the results of thermal conductivity. The highest value of thermal conductivity was obtained for composition B75 (0.279 W/(m.K)), which was very close to composition B50 (0.269 W(m.K)), while the lowest was for specimen B0 (0.233 W/(m.K)), although within the variation of B25. It can be observed that thermal conductivity increases with the proportion of banana fibres that replace wood particles.

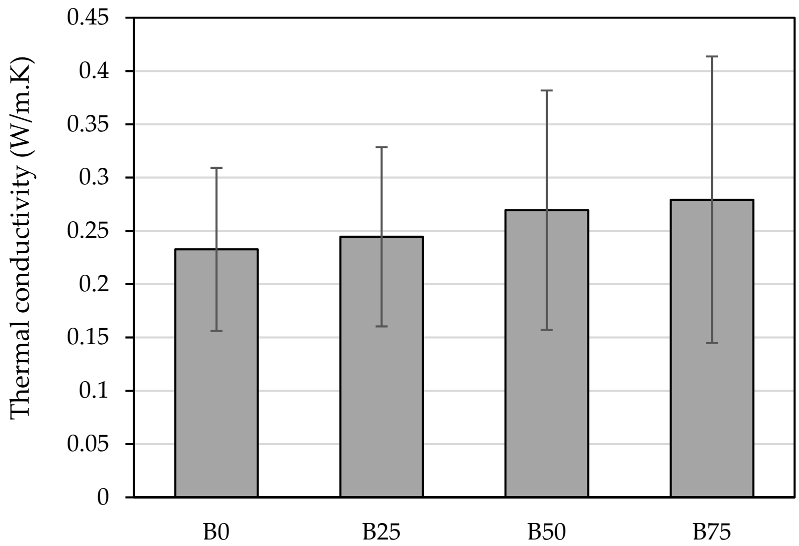


Figure 4. Average thermal conductivity results.

Comparing the values of the present study with the literature, it is possible to say that the thermal conductivity of the presently produced CBPB samples is not only lower than that of concrete boards, with values of 1.52 ± 0.03 W/(m.K) but also lower than some wood particleboards, with values of 0.29 ± 0.01 W/(m.K) [38,47]. However, Park et al. [48] obtained lower thermal conductivity values ranging between 0.074 W/(m.K) and 0.108 W/(m.K) for boards made of wood, cement, and lime, whereas Wang et al. [49] reported values of 0.10 W/(m.K) and 0.14 W/(m.K) for cement-bonded particleboards with grapevine stalk particles.

3.2. Bulk Density

The results of bulk density are shown in Figure 5, with completely dried cut specimens (Table 2). Specimens B50 and B75 present the highest average bulk densities (1995 kg/m^3 and 1948 kg/m^3, respectively). As can be seen, the values of bulk density increase with the proportion of banana fibres, which indicates the greater compactness of the CBPB. This can be justified by the different loose bulk density of the wood in comparison to the banana pseudostem fibres, corresponding to different added volumes when wood was replaced by banana tree fibres. For maritime pine, bulk densities ranging between 530–600 kg/m^3 have been presented [50], whereas Idicula et al. [51] obtained a value of 1350 kg/m^3 for banana fibre. Part of this difference can be justified by the filler resulting from the banana pseudostem milling that can be observed by the particle size distribution of this material (Figure 1). Specimens with 0% banana tree fibres (B0) obtain the lowest bulk density (1754 kg/m^3), corresponding to a decrease of 21 kg/m^3 when compared to the highest value, obtained for B50 specimens.

Rocha Almeida et al. [24] obtained lower values of bulk density, in the range of 1200–1400 kg/m^3, for babaçu coconut shell CBPB, while Macêdo et al. [52] also obtained lower values of bulk density, between 1330 kg/m^3 and 1557 kg/m^3, for CBPB produced with the waste wood of six Amazon hardwood native species. Atoyebi et al. [9] observed values of loose bulk density between 1052-1639 kg/m^3 for particleboards made of wood sawdust, cement, and palm kernel shell (PKS), whereas Park et al. [48] obtained values between 876 kg/m^3 and 984 kg/m^3 for wood-lime boards. Comparing these results with the ones obtained in the present study, it is possible to observe that cement wood particleboards with banana pseudostem waste present higher values of bulk density.

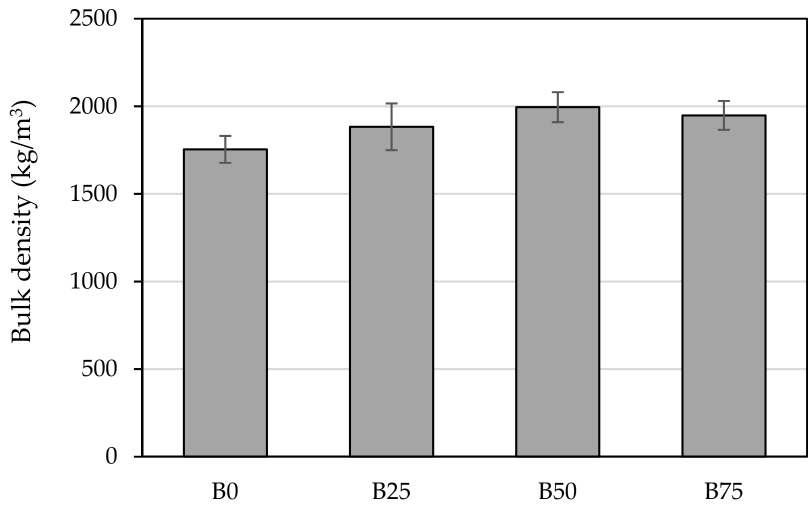


Figure 5. Average bulk density results.

Considering the strong dependence between thermal conductivity and bulk density obtained in previous studies [53–55], the results of thermal conductivity are in line with those obtained for bulk density. A higher density of CBPB induced fewer voids, thus leading to higher thermal conductivity [2]. Figure 6 shows the values of density plotted against the thermal conductivity (Figure 6a). The results are also in agreement with a naked-eye visualization of the samples' cut surface, which shows that the voids' prevalence decreased with the replacement of wood particles by banana tree waste, at least up to 50%; past that amount, visual differentiation was not possible.

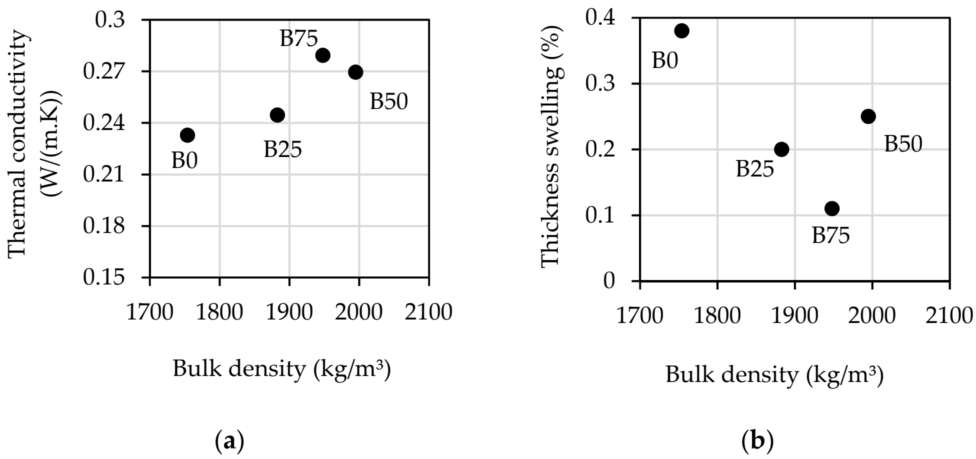


Figure 6. Comparison: (**a**) between bulk density and thermal conductivity; (**b**) between bulk density and thickness swelling.

3.3. Dimensional Stability

The thickness swelling was determined after 24 h of water immersion, and results are presented in Figure 6b and related to the bulk density. Specimens B0 (without banana pseudostem fibres in its composition) show the highest thickness swelling (0.38%). Thickness swelling seems to decrease with the substitution of wood particles by banana fibres (B25 at 0.20%; B50 at 0.25%) with the lowest thickness swelling recorded for B75 specimens (0.11%).

This thickness swelling decrease with the replacement of wood particles by banana fibres can be justified by either a larger volume of voids in the full wood CBPB with lower values of density and greater water absorption or the hygroscopicity of wood, which also needs to be considered, because the free OH groups of the cellulose contact with water and form hydrogen bonds [2,56]. It seems that lower density is caused by a lower number of voids but also by improved bonding between cement, wood, and banana fibres, contributing to lower thickness swelling. Similar results were found by Cavdar et al. [26] by adding black sludge into CBPB composition instead of grey sludge and by Rocha Almeida et al. [24], who observed that lower density leads to higher thickness swelling due to a greater number of voids that allow water absorption.

He et al. [2] measured the thickness swelling of wood-cement boards with magnesium oxychloride in their composition and obtained values ranging between 0.11% and 0.44%, whereas Okino et al. [11] tested a mixture of eucalypt and rubberwood in CBPB composition and obtained higher values of thickness swelling, in the range 1.5–1.8%. Rocha Almeida et al. [24] reported values of thickness swelling between 0.15% and 0.27%. The result of thickness swelling obtained in the present study for specimens B0 is lower than those obtained by Okino et al. [11], slightly higher than those reported by Rocha Almeida et al. [24], but in the range of those obtained by He et al. [2].

3.4. Biological Susceptibility to Moulds

The results of the average rate of mould growth for sanded and unsanded CBPB surfaces are summarized in Table 4. No growth was detected during or at the end of the 4 week testing for unsanded surfaces. This can be due to the high alkalinity of the boards, with documented pH ranges between 11 and 13, which limits fungal colonization and development [5,12,46], and also by the fact that wood and/or banana fibres are not directly exposed to the fungi, being fully encapsulated by the cement paste.

Table 4. Average rate (± standard deviation) of mould growth (n = 3).

Specimens		Mould Development			
		Week 1	**Week 2**	**Week 3**	**Week 4**
Unsanded surface	B0u	0	0	0	0
	B25u	0	0	0	0
	B50u	0	0	0	0
	B75u	0	0	0	0
Sanded surface	B0p	0	0	0.33 ± 0.58	0.33 ± 0.58
	B25p	0	0	0.33 ± 0.58	0.33 ± 0.58
	B50p	0	0	0.33 ± 0.58	0.67 ± 0.58
	B75p	0	0.33 ± 0.58	0.67 ± 0.58	0.67 ± 0.58
Viability control (maritime pine)	C (pw)	3.33 ± 0.58	4	4	4

Scale: 0—no growth; 1—traces of growth; 2—light growth; 3—moderate growth; 4—heavy growth.

When considering the sanded surface specimens, the maximum rate of mould growth was obtained between the third and the fourth weeks of exposure, though only traces of growth (grade 1) were registered. Similar results were observed by Okino et al. [12], who only detected a slight presence of mycelium in the surface of CBPB composed of treated cypress particles. However, in the present study, the replacement of pine wood particles by banana fibres slightly increased the CBPB biological susceptibility (Table 4).

All the controls (maritime pine) were rated as 4 from the second week of testing (Table 4), which confirms the validity of the test.

4. Conclusions

In this study, the viability of producing cement-bonded particleboards (CBPB) with increasing replacement of pine wood particles with banana pseudostem waste fibres was assessed, opening a new option to manage this waste. Test specimens were produced assuming 0%, 25%, 50%, and 75% partial replacement of wood particles with banana pseudostem fibres. The bulk density, thermal conductivity, and dimensional stability of the different specimens were assessed. The immediate (unsanded surfaces, reproducing new boards) and long-term (sanded surfaces, reproducing weathered ones) mould susceptibility of the boards was also investigated. The following conclusions can be drawn:

- The thermal conductivity of the CBPB increased with the replacement of wood by banana fibres and ranged between 0.233 W/(m.K) and 0.279 W/(m.K).
- The bulk density values, ranging between 1754–1995 kg/m^3, were generally higher than those reported in the literature for other particleboards. Moreover, the bulk density generally increased with the proportion of banana fibre, being the highest value obtained for CBPB with an equal proportion of wood particles and banana fibres.
- Specimens with a higher percentage of banana fibres presented less thickness swelling and higher dimensional stability.
- Although cement-bonded particleboards with unsanded surfaces showed no signs of biological growth, the boards with sanded surfaces simulating some surface wear over time had increased bio-susceptibility. Under the conditions of the test performed, the biological susceptibility to the moulds *A. niger* and *P. funicullosum* of the boards slightly increased with the percentage of banana fibres.

The results demonstrate the viability of producing cement-bonded particleboards with partial replacement of raw pine wood fibres by a waste, namely banana pseudostem fibres. Further studies are necessary to optimize the composition of the boards, as well as to evaluate their mechanical properties. The production process can also be optimized, thus allowing the implementation of these innovative cement-bonded particleboards by the industry.

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