



Article

Thermal and Mechanical Properties of Green Insulation Composites Made from *Cannabis* and Bark Residues

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Abstract: The objective of this paper was to investigate the technical feasibility of manufacturing low density insulation particleboards that were made from two renewable resources, namely hemp fibers (*Cannabis sativa*) and pine tree bark, which were bonded with a non-toxic methyl cellulose glue, as a binder. Four types of panels were made, which consisted of varying mixtures of tree bark and hemp fibers (tree bark to hemp fibers percentages of 90:10, 80:20, 70:30, and 60:40). An additional set of panels was made, consisting only of bark. The results showed that addition of hemp fibers to furnish improved mechanical properties of boards to reach an acceptable level. The thermal conductivity unfavorably increased as hemp content increased, though all values were still within the acceptable range. Based on cluster analysis, board type 70:30 (with 30% hemp content) produced the highest mechanical properties as well as the optimal thermal conductivity value. It is concluded that low density insulation boards can be successfully produced using these waste raw materials.

Keywords: insulation composites; thermal properties; mechanical properties; *Cannabis*; hemp; bark



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1. Introduction

Building owners have become interested in a sustainable and healthy environment, which is a trend favoring ecological materials with outstanding performance. In addition, nowadays, thermal insulation can be considered to be a hot issue for civil engineering that tries to reduce cooling and heating costs and, at the same time, eliminate CO₂ emissions [1,2]. Insulating materials are produced for a variety of applications and with specific properties, based on their end use. Thermal conductivity is the most crucial property, followed by fire behavior and compressive strength [3]. The main products, which are available in the market for heat insulation materials, can be categorized, as follows: (i) synthetic materials, like polyurethane and polystyrene; (ii) inorganic materials, like mineral wool and glass. However, the recycling of such products is problematic since their degradation is quite slow and generates toxic substances [4]. In addition, the standards for contaminant emission as far as the building materials are concerned are significantly extended and, therefore, the impact of human's exposure to unhealthy materials is an important parameter that has to be taken into consideration [5]. A third, and perhaps more attractive option, is materials produced from renewable resources, which have gained increased popularity in recent years [6–12]. These may include wood residues, agricultural residues, and tree barks.

Various lignocellulosic materials have been used to manufacture low density insulation composites. Panyakaew and Fotios [1] produced low density binderless thermal insulation boards made from coconut husk and bagasse. They found that the bagasse insulation boards provided mechanical properties that were superior to those of coconut husk

boards; on the other hand, the binderless coconut husk insulation boards showed greater stability against water. It was also reported that thermal conductivity values of boards that were made from this type of raw material were close to those of conventional insulation materials. Doost-hosseini et al. and Taghiyari et al. [2,13] manufactured insulation boards from sugar cane bagasse, and reported on the correlation between the physicommechanical properties and the permeability of the boards and the sound absorption coefficients. Low correlations were found between the sound absorption coefficients and physicommechanical properties, and it was concluded that sound absorption coefficients cannot be considered to be a reliable criterion to predict the board performance. Ibraheem et al. [14] developed insulation boards that were fabricated from polyurethane reinforced with kenaf fibers, at three different weigh contents. They reported the optical performance of boards at a weight of 50% kenaf fibers. In addition, it was stated that the thermal conductivity decreased with an increasing fiber content.

Tree bark, which is a byproduct of the timber industry, has also been applied for the manufacture of low density insulation properties. Bark is used mainly for low-value applications, such as a soil covering material in agriculture or as a fuel. It was reported that the thermal conductivity of bark is approximately 20% lower than that of solid wood [15]. Furthermore, bark is suggested as an insulation material due to its flame retardant properties, its favorable internal structure, and its low density [16,17]. Kain et al. [8] made insulation boards from particles of larch bark, which were bonded with a tannin resin. It was found that the resin amount did not significantly influence the mechanical properties, but the panel density was reported to be the most important variable. It was also reported that light boards had a low thermal conductivity value. Recently, thermal insulation panels were made from various bark species (larch, pine, spruce, fir, and oak tree bark) and bonded with different resin systems (urea formaldehyde, melamine formaldehyde, Quebracho, Mimosa) [18]. It was found that all bark species were suitable for insulation panel production, while, at the same density, panels from barks with a low bulk density (i.e., pine and larch) are advantageous, because their compression ratios are higher, which improves the mechanical characteristics.

Tree bark has already been used within a wood-based sandwich panel, thereby proving its insulation properties [19]. Single layer bark insulation boards have also been constructed in laboratories, demonstrating that bark is a promising new insulation material [18]. On the other hand, hemp has been used as insulation material, together with wood, where the hydrothermal performance was studied. The thermal performance of this board was also competitive with an average thermal transmittance of 0.30 W/mK when compared to existing commercial oil based insulation panels [20]. Ninikas et al. studies the thermal properties of insulation boards that were made of hemp residues and tree bark [21]. However, their mechanical properties were not addressed, and the determination of the thermal conductivity was based on a different measurement setup, as described later in the paper.

Consequently, the objective of this paper was to investigate the technical feasibility of manufacturing low density insulation particleboards that were made from two renewable resources, namely hemp fibers (*Cannabis sativa*) and pine tree bark, bonded with a non-toxic methyl cellulose glue, as a binder.

2. Materials and Methods

2.1. Raw Material

The raw material that was used in this study, namely hemp fibers and pine tree bark, was collected from forest and cropland in Karditsa city, Central Greece. The bark was chipped by a mechanical hammer-mill chipper with a 18 and 20 mm round hole screen (Figure 1a). At least 92% of the bark particles were below 19 mm. The hemp fibres were manually cut with a pair of scissors into approximately 0.10 m length stripes to better bond with the bark (Figure 1b). At least 95% of the hemp fibers were 0.10 mm in length. The orientation of the hemp fibres was random at all three axes (X, Y, Z) when mixed with the bark. It was hypothesised that, for the composite boards, the geometry of the hemp

fibres should be such to assist in bonding the two materials together due to the absence of a hot press. The bark went through a 20 mm diameter sieve (Figure 2a). The aim was to have bark flakes at a size that would accommodate the bonding with the hemp fibres with the minimum gap between the two materials that result in a robust final composite. The average bark consisted of an irregular shaped flake approximately of 0.013–0.018 m (Figure 2b). Bark and hemp fibers were both dried at 105 °C for 24 h to reach 6.5–7% moisture content.



Figure 1. Pine tree bark (a) and hemp fibers (b).

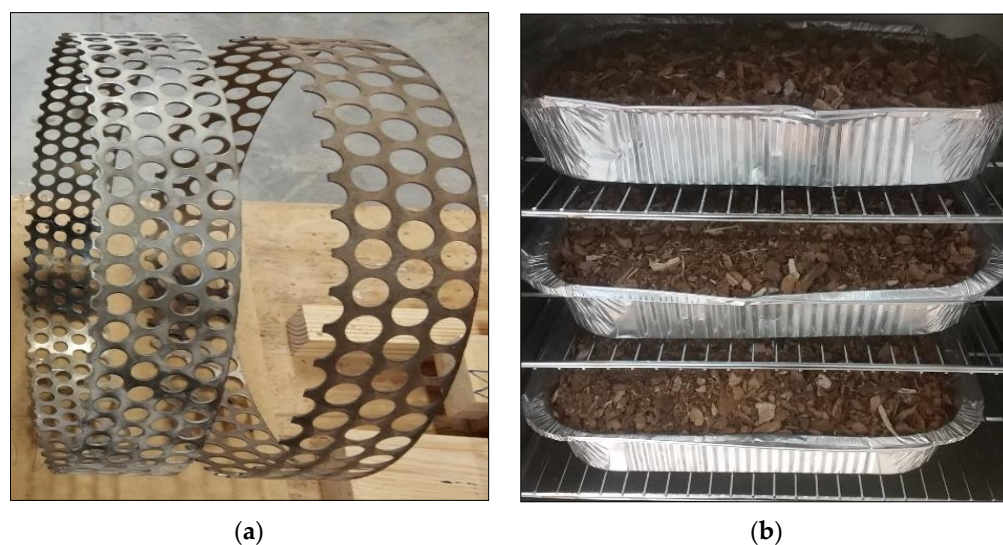


Figure 2. The 18 mm (left) and the 20 mm (right) sieves used for the bark flakes (a) and the bark flakes after the sieving at the moisture chamber (b).

2.2. Board Manufacture

A non-toxic methyl cellulose glue, 4% as a percentage of the oven dry weight of raw material, was applied for single layer board manufacture. The glue (Glutolin N standard wallpaper adhesive, density 0.31 g/cm³, and pH 7–8) was a hydrophilic white powder that dissolved in water at room temperature. According to the supplier, the solution was of 1.25% glue (dry powder). The solution was stirred for 15 min. and then sprayed into the two ingredients while they were mixed together before being placed in to 0.40 m × 0.40 m cast, as depicted in Figure 3. The casts were covered with flat fibreboards and tightened with hand clamps without any mechanical pressure in order to form the

final board thickness of 0.047 m. The composites stayed under these conditions for 48 h at an average room temperature of 23 °C before being opened. Four types of panels were made, which consisted of varying mixtures of tree bark and hemp fibers (tree bark to hemp fibers percentages of 90:10, 80:20, 70:30, and 60:40); an additional set of panels was made, consisting only of bark, as shown in Figures 4 and 5. Three replicates were made for each board type. Target board density was 0.25 Kg/m³.



Figure 3. The resinated raw material.



Figure 4. Particleboards made from varying mixtures of tree bark and hemp fibers (70:30 left and 60:40 right).

2.3. Determination of Mechanical Properties

The boards were conditioned one week at 20 °C and 65% relative humidity prior to testing mechanical properties, namely the modulus of rupture (MOR) and modulus of elasticity (MOE) [22]. The 50 by 350 mm long beams were tested in third-point loading at a span of 320 mm at a loading rate of 3 mm per minute. The load and deflection were continuously recorded, and the resulting data were used to calculate the modulus of rupture (MOR) and modulus of elasticity (MOE).



Figure 5. Particleboards made from varying mixtures of tree bark and hemp fibers (80:20 left and 90:10 center) and panels consisting only of bark (right).

2.4. Determination of Thermal Conductivity

After taking out of the casts, the boards were directly forwarded to the thermal conductivity apparatus without being placed in a furnace to further reduce their moisture content. This was based on a more realistic approach, where the insulation boards do not usually have the ideal moisture content during the installation. This approach was different as compared to the one followed in a previous publication [21], where the thermal conductivity was measured in very dry conditions having the boards in a furnace, at a temperature of 103 °C for several hours, and, therefore, resulted in low values.

For the determination of the thermal conductivity of the boards, the ‘box method’, based on EN ISO 12,667, was applied [23]. For this purpose, a single box of EI-700 unit was used [24], as depicted in Figure 6, which measures the thermal characteristics of homogeneous or heterogeneous, solid, or liquid materials with a comparatively low conductivity ($\lambda < 3 \text{ W/mK}$). The specimens were $0.27 \text{ m} \times 0.27 \text{ m} \times 0.047 \text{ m}$ (length $\times$ width $\times$ thickness). Two temperature probes have been applied, one for the upper (T_{uf}) and one for the lower (T_{lf}) board’s surface temperatures, respectively. The room temperature was also recorded (21 °C). Having the samples within the ‘box’ for approximately 2 h, the temperature was stabilised and the readings for each probe were noted. The ‘box method’ produced readings with regard to the thermal conductivity value of all the insulation boards keeping each of them under stable thermal conditions for 24 h.



Figure 6. The EI-700 unit “box method” for the thermal conductivity measurements.

The thermal conductivity value was calculated based on the following equation:

$$\lambda = \frac{q_{in} * \Delta_x}{A * (T_{uf} - T_{lf})} \quad (1)$$

where

λ the thermal conductivity value (W/m*K)

q_{in} the heat flow from the indoor environment to the 'box' (W)

Δ_x the board's thickness (m): (0.047 m)

A the board's surface (m²): (0.27 × 0.27 = 0.0729 m²)

T_{uf} the temperature at the upper surface of the board (°C)

T_{lf} the temperature at the lower surface of the board (°C)

The heat flow at a steady state is:

$$q_{in} = q_{out} + q_{spl} \quad (2)$$

where

q_{out} the heat flow from the "box" back to the environment (W)

q_{spl} the heat flow through the composite (W)

The heat flow (q_{in}) derives from the equation: [25]

$$q_{in} = \frac{V^2}{R} \quad (3)$$

where

q_{in} the heat flow emitted by Joule effect (W)

V the electric voltage of the device $V = 39.8$ Volt

R the device's resistance (Ω -Ohm) – $R = 1160 \Omega$

All the above parametres are displayed in Figure 7. The grey rectangle at the bottom of the Figure, represents the insulation board, the "blue Π " illustrate the Unit's box.

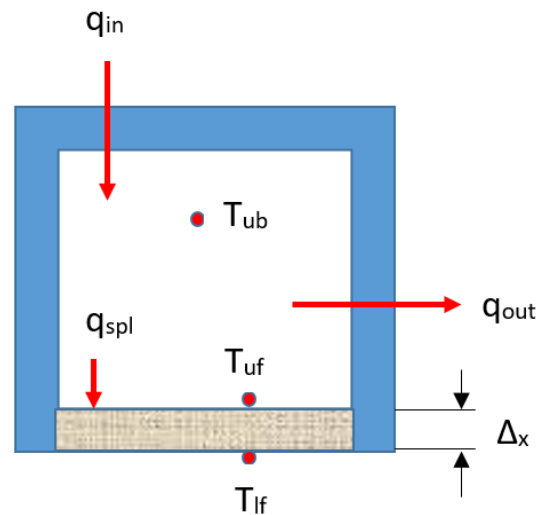


Figure 7. Schematic representation of the 'box'.

2.5. Statistical Analysis

Statistical analysis was conducted using the SPSS software program, version 24.0 (IBM, Armonk, NY, USA, 2018). One-way ANOVA was performed for identifying significant difference at the 95% level of confidence. Duncan's multiple range test grouping was carried out at 95% level of confidence, for each and every property measured, in order to discern significant difference among the five different panels produced and studied here. Contour and surface plots were designed using Minitab statistical software (version 16.2.2;

2010). Hierarchical cluster analysis was carried out based on all of the properties measures in this study, using Ward's method, in order to sum up similarities and dissimilarities among the five types of boards. In this analysis, the number of treatments (here, the number of five different panels) studied are shown as "Num". Subsequently, they are connected based on a scale-bar on top of the analysis, showing numbers from 0 to 25. If treatments are connected by vertical lines on the lower numbers (in terms of the scale-bar), which means that they have more similarities. Going further away on the scale-bar upto 25 means the treatments have more dissimilarities. Cluster analysis demonstrates similarities and dissimilarities among treatments based on all properties that have been studied, giving a better overall outlook on all treatments.

3. Results and Discussion

3.1. Mechanical Properties

The moisture contents of the five types of insulation boards varied from 5.40 to 6.15%. Table 1 shows the mechanical properties of the single layer particleboards made from various tree bark/hemp fibers combinations. At this point, it has to be mentioned that preliminary tests revealed that it was not feasible to manufacture boards with higher hemp fiber content (tree bark to hemp fibers percentages of 50:50, 40:60), since this attempt lead to non-consistent boards. From the data that are presented in Tables 1 and 2, it can be seen that higher hemp fiber levels resulted in two opposing effects. From one side, the thermal conductivity increased as hemp content increased, although all of the values still remained within the acceptable range. From the other side, lack or low hemp contents (0, 10, and 20%) resulted in very low mechanical strength, so that the MOR values of these boards were literary unacceptable by the industry. Therefore, these board types (100:0, 90:10, and 80:20, as described in Table 1) cannot be recommended to the industry. The reduction in bending properties in boards, as the content of the hemp fibers is increased, can be attributed to the fact that hemp fibers is mainly comprised of relatively thin, short-walled, and weak cells [26]. As a consequence, hemp fibers are relatively weak and vulnerable to 'critical defects' inside the board structure and, therefore, a deterioration in bending properties is observed.

Table 1. Mechanical properties of various board types. Standard deviations in parentheses. Different letters show which values are statistically different at the 5% level.

Board Type (Tree Bark: Hemp Fibers)	Density ¹ (Kg/m ³)	Weight of the Raw Material (g)		MOR ¹ (N/mm ²)	MOE ¹ (N/mm ²)
		Bark	Hemp		
100:0	0.24 A ³ (0.02) ²	1660	0	0.01 C (0.01)	0.02 B (0.21)
90:10	0.24 A (0.02)	1440	160	0.01 C (0.01)	0.03 B (0.31)
80:20	0.23 A (0.02)	1280	320	0.09 B (0.01)	1.00 B (0.11)
70:30	0.22 A (0.02) ²	1120	480	0.18 A (0.02)	2.25 A (0.31)
60:40	0.24 A (0.02)	960	640	0.15 A (0.01)	1.90 A (0.19)

¹ Each value is the mean of eight replicates. ² Standard deviation. ³ Values followed by the same letter do not differ significantly from each other by a Duncan's multiple range test ($\alpha' = 0.05$).

The mechanical properties of the present particleboards were comparable to those of other low-density particleboards (100–500 Kg/m³) produced from renewable resources (e.g., kenaf core, bagasse), reporting MOR values between 0.85 and 7 N/mm² and IB (Internal Bond Strength) values between 0.02 and 0.17 N/mm² [27,28]. A potential increase in the bending properties can be achieved through the increase of panel density. A recent study reported on thermal insulation panels made from various types of bark bonded with

a variety of resins, with density values ranging from 0.25 to 0.50 Kg/m³ [18]. The results of the physical-mechanical testing were analyzed using a multivariate ANOVA, and the panel density was considered as a covariate in the statistical model. It was found that bending properties, namely MOR and MOE, are highly affected by the panel density, type of the bark, and type of the resin. It is further reported that almost 60% of the variation in bending properties were attributed to the difference in density values, and that resin content did not show a significant effect on bending properties. It is interesting to mention that MOR and MOE were increased by 0.7 and 140 N/mm², respectively, with a density increase of 100 Kg/m³ [18]. According to the results that were reported by Kain et al. [18], an approach to increase the bending properties of the boards made in this study, is to increase the density of the board.

Table 2. Thermal conductivity values of various board types. Standard deviations in parentheses. Different letters show which values are statistically different at the 5% level.

Board Type (Tree Bark: Hemp Fibers)	Thermal Conductivity Value ¹ (λ) (W/m ² *K)
100:0	0.076 A ³ (0.04) ²
90:10	0.081 A (0.02)
80:20	0.087 A (0.02)
70:30	0.094 B (0.02)
60:40	0.111 B (0.03)

¹ Each value is the mean of three replicates. ² Standard deviation. ³ Values followed by the same letter do not differ significantly from each other by a Duncan's multiple range test ($\alpha' = 0.05$).

3.2. Thermal Conductivity

Table 2 depicts the thermal conductivity (λ) values of the produced insulation boards. From this, it can be seen that boards made only from bark demonstrated better (lower) thermal transmittance value as compared to the boards containing various amounts of hemp fibers. The bark-based insulation boards showed a thermal conductivity value of 0.076 W/m²*K, which is in accordance with values that were reported in the literature [18] and higher than those of very light insulation boards (e.g., polystyrene, mineral wools with approximately 0.03 W/m²*K). This disadvantage is compensated for by the low thermal diffusivity of bark [16,18]. This makes the material suitable for use as insulation layers that need to prevent quick cooling or overheating during summer.

A closer inspection of the data that are depicted in Table 2 reveals that the increase in hemp content resulted in higher thermal transmittance values and, furthermore, it is worth to be mentioned that the incorporation of hemp fibers up to 20%, did not significantly affect the thermal transmittance of the boards. This is in agreement with Ibraheem et al. [14], who developed insulation boards that were fabricated from polyurethane reinforced with kenaf fibers. They reported optimal performance of boards at a weight of 30% kenaf fibers. In addition, it was stated that the thermal conductivity decreased with increasing fiber content. The increased thermal conductivity values, as the content of the hemp fibers is increased, can be attributed to the high void content in the final panel [29]. Small pores are advantageous in this respect, because the air in such voids is static, and heat convection has a minor effect [30,31]. The existence of plenty of voids was also reported to improve sound absorption coefficients in insulating boards made from bagasse [32,33].

The different results for the thermal conductivity (for the 70:30 and 60:40 boards) that were obtained in this study in comparison with the previous study [21] are due the different measurement setup. In that study, the thermal conductivity was the one measured in very dry conditions having the boards at a furnace, at a temperature of 103 °C for several

hours. In this study, it was chosen to identify the thermal conductivity readings without positioning the boards to a furnace that would reduce the moisture content even more as it happened herein. This means that the boards in this study were not so “dry” as in the previous study [21]. This explains the higher values (worst performance) as compared to the results reported by Ninikas et al. [21] for these two types of boards (70:30 and 60:40). This process was followed to all boards at this study and was based on a more realistic approach where the insulation boards do not have the ideal moisture content during the installation.

All types of boards resulted in acceptable thermal conductivity values, based on the value $\lambda < 1.15 \text{ W/m}^2\text{K}$, which is considered to be the limit for an appropriate insulation material [34]. In this connection, contour and surface plots between thermal conductivity versus different properties studied here demonstrated a clear relationship among properties within the acceptable range, although some minor discrepancies were also seen (Figure 8A,B). The discrepancies were attributed to the opposing effects of the addition of hemp on different properties. That is, the hemp content tended to increase thermal conductivity, as explained earlier; however, its delicate inter-connecting texture helped to ensure better integrity within the furnish, and ultimately the mechanical strength improved with higher hemp contents.

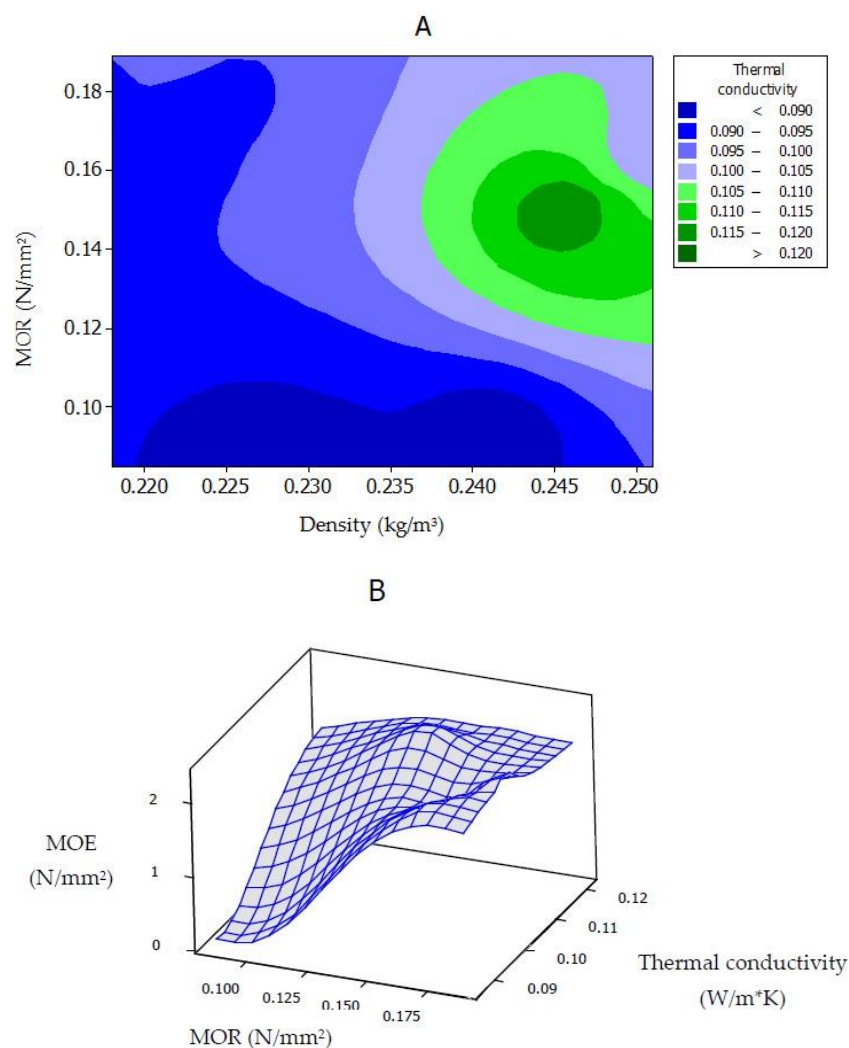


Figure 8. Contour (A) and surface (B) plots among different properties (thermal conductivity in $\text{W/m}^2\text{K}$, MOR in N/mm^2 , MOE in N/mm^2 , and density in kg/m^3 values) within the acceptable range in the insulating boards made from *Cannabis* and bard residues.

A major issue addressed in this paper was to produce low density insulation boards from renewable resources, namely hemp fibers (*Cannabis sativa*) and pine tree bark. The use of a non-toxic methyl cellulose glue, formaldehyde-free, was a further challenge. The energy requirements (energy input) for constructing the five board types in this study, were kept relatively low due to the little energy input during the production procedure. The energy input for these boards was due to (a) the drying procedure (chamber) that was used for 24 h to reduce the moisture of the raw materials and (b) chipping procedure for the mechanical hammermill. Usually, the manufacturing procedure for a typical insulation board, with regards to the energy input during the production line, is immense due to the nature of the basic ingredients (petrol-based materials) [35]. The dimensional stability and biological durability of the panels produced in this study was not assessed, since the aim of the work was to produce low density insulation boards with an environmental friendly-non toxic adhesive. In such types of panels, these two properties are of minor importance. However, studies that are related to the manufacture of boards with these waste materials (bark and hemp), with higher density value and bonded with conventional formaldehyde resins, are under way and the results will be reported in due course.

Cluster analysis based on all of the properties measured in the present study categorized the five types of insulating boards, as depicted in Figure 9. It was demonstrated that all board types with hemp contents of lower than 20% were clustered very closely together; they are connected by vertical lines of less than digit “5” in terms of the scale-bar on the top of the graph. The other two board types with hemp contents of 30% and 40% (board types 70:30 and 60:40, as defined in Table 1) clustered very remotely from the other three types; as illustrated, they are connected by a vertical line on digit “25” in terms of the scale-bar. This was in close agreement with the low and unacceptable mechanical strength of the first three board types, as explained earlier. Cluster analysis also illustrated different clustering of the two board types with hemp contents of 30% and 40% (connecting to each other on digit “10” in terms of scale-bar). By taking the mechanical properties and thermal conductivity values into consideration (Tables 1 and 2), it can be deduced that board type 70:30 produced the optimal properties that can be recommended to the industry.

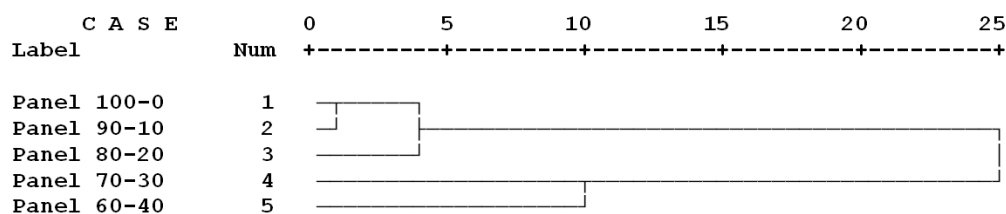


Figure 9. Cluster analysis of the five insulating board types, based on all properties measured (Num = number of five panels studied, based on the label column).

Low density insulation boards have been successfully produced using these waste raw materials. Their potential application can contribute to the reduction of cooling and heating costs and, at the same time, eliminate CO₂ emissions. The limited energy demand for the construction of these board types is expected to improve the carbon footprint of the insulation board and address a financially viable solution for producers who currently direct the residues in landfills with an additional cost.

4. Conclusions

This paper examined the technical feasibility of manufacturing low density insulation particleboards that were made from two renewable resources, namely hemp fibers (*Cannabis sativa*) and pine tree bark, which were bonded with a non-toxic methyl cellulose glue, as a binder. It was found that higher hemp fiber levels resulted in an increasing trend in thermal conductivity of boards, although all board types were still within the acceptable thermal conductivity range when compared to the value $\lambda < 1.15 \text{ W/m}^2\text{K}$ which is considered to be the limit for an appropriate insulation material. Mechanical properties of boards

with no or low hemp contents (0, 10, and 20% hemp) were not acceptable for the industry, although these produced the lowest thermal conductivity values. Based on the cluster analysis, it was concluded that board type 70:30 produced the boards with the highest mechanical properties and the optimal thermal conductivity. Therefore, using these waste raw materials for the production of insulating boards can be recommended.

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