Insulation Properties of Boards Made from Long Hemp (*Cannabis sativa* L.) Fibers

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Long fibers from fast growing hemp (*Cannabis sativa* L.) were used as a raw material for the production of insulation boards in this preliminary work. Hemp fiber boards with densities that ranged from 300 kg/m^3 to 1100 kg/m^3 were studied. The boards were pressed as one- or three-layered structures. In the three-layered structure, the core was formed of hemp fibers and the outer layers were manufactured from 1.5-mm thick birch veneers. The basic insulation properties of the boards were tested. The heat transfer coefficient value for the boards without veneers allowed this material to be classified as an insulating material. Although the additional veneer layers significantly impaired the heat transfer coefficient, its value was still lower than that of standard wood-based board materials with a similar density. The produced boards were characterized as having good noise reduction properties. The acoustic insulation factor was higher compared with boards intended to be used as thermal insulation, such as mineral wool or light fiberboards with four times greater thicknesses.

Keywords: Hemp; Boards density; Physical properties; Insulation properties

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INTRODUCTION

In recent years, there has been an increasing societal awareness of the need for environmental protection and sustainable use of natural resources. This has been accompanied by an escalating level of urbanization and climate change that limits the possibilities for the use of land for agricultural or forestry purposes. However, the observed rising deficit in the wood supply has not necessarily led to a reduction in the demand for goods produced from wood. Economic competitiveness at local and global levels noticeably contributes to a search for solutions that meet the societal demand for products manufactured from wood. Wherever possible, solid wood products are being replaced with wood-based materials. An increase in the production of wood-based materials has been observed for nearly one hundred years (FAO 2017). However, the most noticeable changes in the production of wood-based materials have occurred during the last 30 years. While the manufacturer market is dependent on its raw materials base, the customer market knows no such boundary. For these reasons, the increasing deficit in the wood supply is not necessarily associated with a decreasing raw materials base in relevant areas. Industry and scientific centers have indicated at least three directions that could reduce the consequences stemming from this situation. The first direction is associated with the production of components that are light or have a reduced density (Tittelein *et al.* 2012; Král *et al.* 2014; Shalbafan *et al.* 2016; Sundquist and Bajwa 2016), and the other two directions focus on the use of wood species not previously used in the production of wood-based materials (Salari *et al.* 2013; Warmbier *et al.* 2013; Gava *et al.* 2015; Taş and Sevinçli 2015; He *et al.* 2016) and on the substitution of wood with particles from plants other than trees

(Müeller *et al.* 2012; Dziurka and Mirski 2013; Zhang and Hu 2014; Dukarska *et al.* 2015; Nazerian and Moazami 2015).

At the moment, only plywood production requires wood in its pure form. All other composites can be and are produced from materials other than wood. Amongst these materials, particular attention has been paid to woody bamboo stems, which are used for numerous applications, excluding plywood production. This material is successfully used to produce boards with cores made of bamboo mats. Another plant that may replace wood in the production of wood-based boards to a relatively wide extent is hemp. Depending on the shredding degree, it can be used to produce particleboards (PBs), insulating mats, and fiberboards. One of the most important advantages of hemp is that this plant easily adapts to its environment. Factors, including the soil conditions, temperature, growing season length, and climate conditions, can affect the development of many varieties of one species, and therefore, it can be found on every continent. In the previous study by the authors (Mirski *et al.* 2017), long hemp fibers were used as a raw material to produce furniture or construction boards. The research showed that depending on the density, long hemp fiber boards could be used in the furniture and construction sectors, as they met the requirements of relevant standards for P2 (650 kg/m^3), P5, and oriented strand boards (above 750 kg/m^3), in terms of their strength. It was also observed that the boards made with hemp fibers were characterized by a relatively good resistance to water, which was manifested as a low degree of swelling and slight susceptibility to water penetration.

Taking into account the results of previously conducted studies and the use of these boards in the construction industry, this study focused on the insulation properties of boards manufactured from long hemp (*Cannabis sativa* L.) fibers with various densities.

EXPERIMENTAL

Materials

The fibers used in this study were hemp fibers for industrial applications supplied by STEICO (Czarnków, Poland), a company that uses these fibers to produce some of its insulating mats. Fibers with a 11% moisture content were glued with pMDI (BorsodChem, Godollo, Hungary). The properties of pMDI were as follows: NCO content: 30.9%, Viscosity at 25 °C: 215 mPa·s, Chlorine hydrolytic: 96 mg/kg. The resin in the amount of 9% of their dry weight was applied with a manual spraying gun (Professional, Genine by Fachowiec, made in Taiwan).

Table 1. Board Markings and Production Conditions

Marking	Veneer	Core Density	Board Density	Pressing Pressure	Press Closing Time	Temperature/ Pressing Time
		kg/m^3	kg/m^3	MPa	s	°C/s
A_3N*	No	300	300	1.8	10	200/225
A_3**	Yes	300	330	1.8	10	
B_5	Yes	400	470	2.0	10	
C_7	Yes	700	630	2.2	15	
D_9	Yes	900	750	2.4	15	
E_11	Yes	1100	900	2.6	20	
F_13	Yes	1300	1110	2.8	20	

* board without birch veneer with density 300 kg/m^3,

** A_3 …. F_13 boards with veneers with densities ranging from 300 to 1300 kg/m^3

The boards were pressed as one- or three-layered structures. In the three-layered structure, the core was formed from hemp fibers and the outer layers were 1.5-mm thick birch veneers. The manufactured boards were 15 mm thick, and the core density ranged from 300 kg/m^3 to 1300 kg/m^3 (Table 1). As the external layers were made of veneer, the board density reflected a relationship between the veneer density (460 kg/m^3 ± 5 kg/m^3) and assumed core density.

Methods

Soundproofing properties

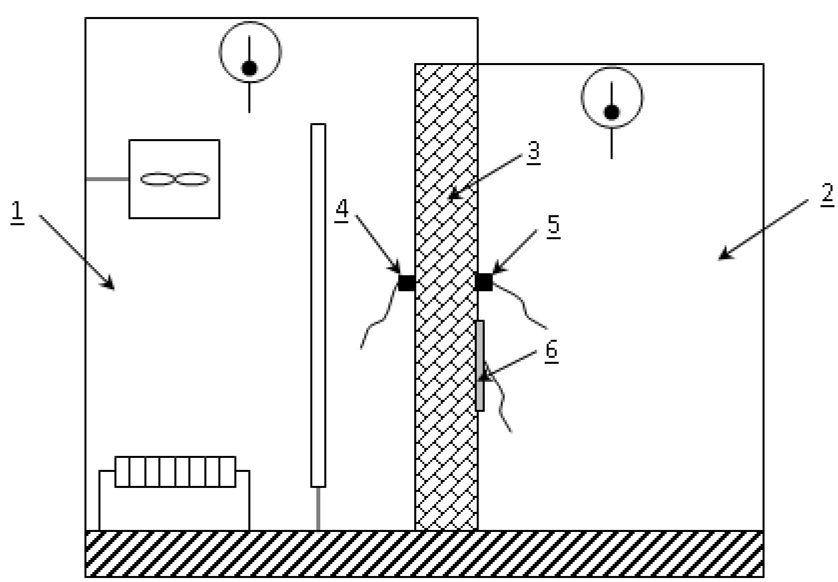
The acoustic chamber used in the tests allowed for the determination of the airborne sound damping degree of the studied materials. The chamber consisted of two parts: an immobile part that acted as a receiving chamber and the other was mobile and played the role of a transmission chamber. The two chambers were separated by the studied material. In the transmission chamber, speakers were installed to generate an acoustic wave with specific parameters. The receiving chamber was equipped with a digital sound meter (Sonometr DT-8852, CME, USA). The whole system was controlled by a computer. The measurements were conducted at frequencies specified in the standard EN ISO 10140-1, which included 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, and 3150 Hz. The obtained results were used to determine the specific acoustic insulation factor (R) for each frequency using Eq. 1,

$$R\ (\text{dB}) = L_1 - L_2 + (\log S - \log A) \qquad (1)$$

where L_1 is the maximum sound pressure in the receiving chamber (dB), L_2 is the sound pressure in the receiving chamber after mounting the tested sample (dB), S is the sample surface area (0.5 m^2), and A is the absorbing surface area of the receiving chamber (2 m^2).

Heat transfer coefficient

The heat transfer coefficient was determined using the measuring system that is shown in Fig. 1.



1 - Heating chamber
2 - Cooling chamber
3 - Sample of the tested material
4, 5- Thermocouples (TypeJ 2x0, 20TT (teflon FEP), Termo Aparatura, Wrocław, Poland)
6 - Heat stream sensor (FQA017C, Somet, Gliwice, Poland)

Fig. 1. Diagram of the measuring system for determining the heat transfer coefficient

The measuring system consisted of two chambers, one for heating and the other for cooling. In the heating chamber, a constant air temperature was maintained and the air was circulated. The continuous air circulation in this chamber ensured a uniform temperature in the whole interior. The cooling chamber was separated from the heating chamber with a sample of the tested material. In this chamber, the air was heated solely through a partition heated on the side of the heating chamber. The heat transfer coefficient (λ) was calculated using Eq. 2:

$$\lambda \text{ (W/mK)} = q \times d / (T_g - T_c) \qquad (2)$$

where q is the heat stream density, which was calculated with Eq. 3:

$$q \text{ (W/m}^2\text{)} = C \times U \qquad (3)$$

where C is the sensor calibration probe (35.8 W/m^{2}mV), U is the voltage (mV), d is the partition thickness (m), T_g is the sample surface temperature (°C) in the heating chamber (thermocouple 4), and T_c is the sample surface temperature (°C) in the cooling chamber (thermocouple 5).

TG and DTG

The susceptibility to thermal degradation was determined by thermogravimetric (TG) and differential thermogravimetric (DTG) analysis at the following conditions: a final temperature of 600 °C, heating rate of 5 °C/min, He atmosphere of approximately 2 dm^3/h, and sample weight of 20.0 mg ± 1 mg.

Flammability

As the manufactured boards were lined with veneers that were not fire-proofed, the veneer was removed before the tests and the samples prepared in this way were tested for ignitability. Samples of the boards (15 cm × 15 cm) were dried at 102 °C ± 3 °C for 24 h. After cooling, the samples were placed on a stand at an angle of 45° in relation to the base. A spirit burner was placed under the stand with a wick 5 cm away from the sample. The flame under the sample was maintained for 3.5 min. After that time, the burner and sample, if burning with a visible flame, were extinguished. The tested samples were weighed before the test, and then again 5 min and 60 min afterwards. A decrease in the sample weight was calculated based on the weight difference. During burning, the sample was monitored for signs of burning or glowing and the time until ignition was recorded. After cooling, the surface area damaged by the flame was determined with a planimeter (HA-317E, Geo Fennel, Germany). A furniture PB with a thickness similar to that of the studied boards (16 mm) and a density of 750 kg/m^3 was used as a reference.

Each test was performed with three or five replicates. Statistical analyses of the data were performed with Statistica 12.0 software (StatSoft Inc., Tulsa, OK, USA).

RESULTS AND DISCUSSION

Figure 2 presents the heat transfer coefficients for the hemp fiber boards. In the case of the boards with veneer, an increase in the heat transfer coefficient with an increase in the density was better described exponentially, rather than linearly. This possibly resulted from the conditions applied during board pressing. However, taking into account a linear function, the boards produced were characterized with lower coefficient values than those of the available lignocellulosic materials. These coefficients are 0.14 W/mK and approximately 0.08 W/mK for PBs or fiberboards with a density of 600 kg/m^3 and for straw or reed insulating boards with a density of 300 kg/m^3, respectively.

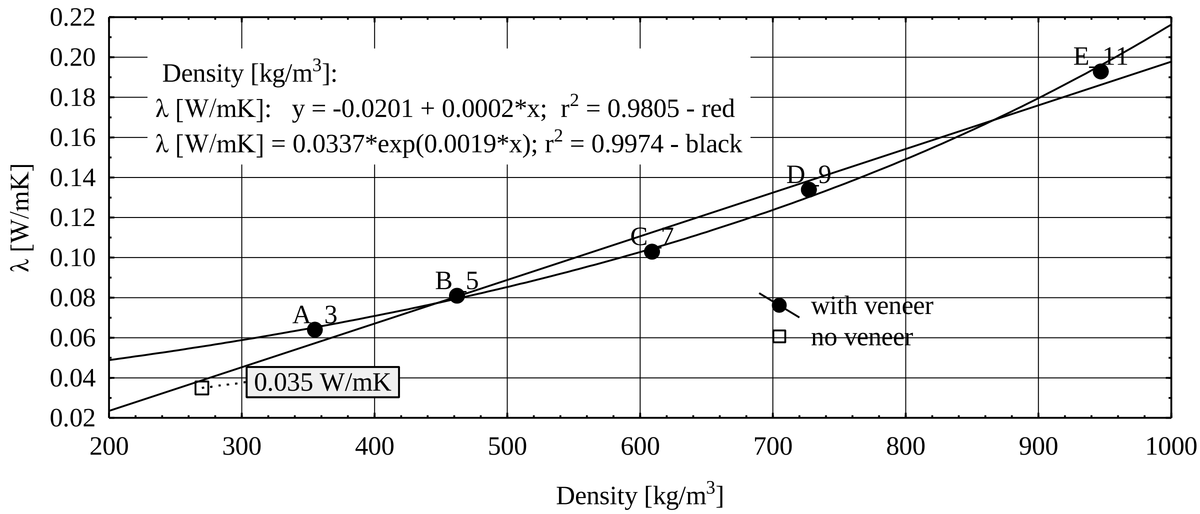


Fig. 2. Effect of the hemp fiber board density on the heat transfer coefficient

When the fitting curve for the hemp fiber boards was assumed to be exponential and at the lowest theoretical density possible to produce a board (150 kg/m^3), the boards should be characterized by a coefficient similar to that of STEICO top boards (density = ~140 kg/m^3, λ = ~0.041 W/mK, Steico). The advantageous heat transfer coefficient determined for the board manufactured without veneers allowed for classifying this board as a high quality thermo-insulating material.

The test determining the noise reduction coefficient showed that this property could not be directly related to the density of the boards manufactured in the laboratory. Table 2 indicates that the boards with the lowest and highest densities, *i.e.*, A_3 and E_11, respectively, were typically characterized by a lower noise reduction effectiveness than the other boards.

Table 2. Noise Reduction Characteristics of the Hemp Fiber Boards

Sound Frequency	Board Type				
	A_3	B_5	C_7	D_9	E_11
Hz	*R* (dB)				
250	4.9	10.4	13.6	18.6	17.4
500	28.9	37.5	38.6	32.5	31.6
1000	33.6	31.3	34.8	35.0	30.6
1250	33.0	35.2	34.9	34.5	29.8
1500	27.2	39.2	38.8	38.0	30.2
2000	19.4	33.4	29.5	31.3	27.0
2500	37.5	45.7	52.2	45.0	41.2

The noise reduction effectiveness strongly depended on the frequency at which the measurement was performed. At a frequency of 250 Hz, the noise reduction effectiveness for the board with a density of 300 kg/m^3 was 12.5 dB lower than that for the board with a density of 900 kg/m^3; meanwhile, at a frequency of 1000 Hz, the noise reduction effectiveness of the board with the lower density was 3 dB better compared with the board with the higher density. For the other boards, the acoustic insulation factor value was higher by approximately 1 dB to 15 dB, which implied better insulation properties for the boards with a density within the range of 470 kg/m^3 to 750 kg/m^3. At a low frequency (250 Hz), the boards produced with hemp fibers and strengthened with veneer as the outer layers were characterized by a noise reduction effectiveness similar to that of cladding and insulating materials, excluding expanded styrene. Significant differences were noted only for higher frequencies. In this case, the hemp boards were characterized by a 30% to 45% better noise reduction effectiveness than that of other materials, such as fiberboard or mineral wool, and a nearly twice as high noise reduction effectiveness as that of the materials analyzed by Dukarska *et al*. (2015) and Smardzewski *et al.* (2014; 2015).

An analysis of the TG and DTG curves indicated a slightly higher thermal resistance of the hemp fibers compared with that of the birch veneer (Fig. 3). The total weight loss at 600 °C was 68.0% for the hemp sample and 72.1% for the birch veneer. However, the maximum decomposition temperature (T_{max}) was nearly 20 °C higher for the wood than for the fiber, which were 356.7 °C and 336.9 °C, respectively. Although the weight loss at the T_{max} was as much as 53.0% for the wood and 40.1% for the fibers, the degree of decomposition was smaller for the wood than for the fibers at 336.9 °C, as its total weight loss reached only 36.5%. This result was caused by a characteristic inflection in the DTG curve from 283 °C to 293 °C, after which the decomposition rate visibly decreased. In this temperature range, observed another local extreme value for oak wood, which was not visible in the thermographs for pine or beech wood. The total weight losses observed at 600 °C reached 72.1%, 73.0%, and 77.3% for oak, pine, and beech wood, respectively. Therefore, potential birch, beech, and pine veneers were characterized by lower thermal resistances (up to 600 °C) than for the hemp fibers. The use of pMDI as a binding agent improved the thermal resistance of the adhesive-coated materials, as its thermal stability was higher than the stability of the fibers or birch wood. The total weight loss was only 30% and 60% at approximately 360 °C and 600 °C, respectively (Dziurka and Mirski 2013).

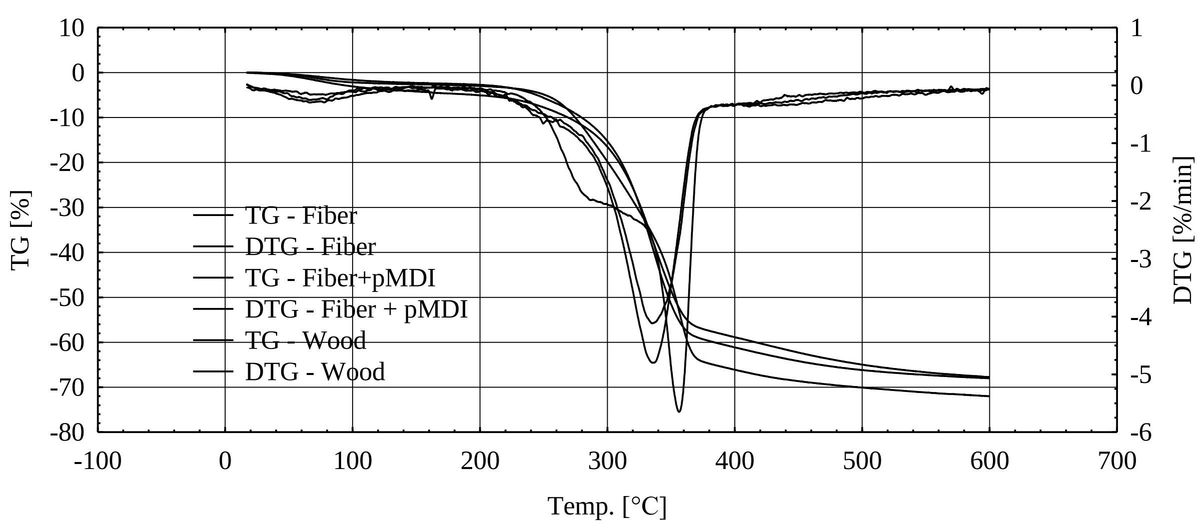


Fig. 3. TG and DTG curves of the hemp fibers, hemp fibers glued with pMDI, and birch veneer

A slightly better thermal stability of the hemp fibers could be potentially reflected in their different behavior when exposed to an open flame. As was indicated by the data presented in Table 3, the ignition time of the hemp boards strongly correlated with the density.

Table 3. Flame Resistance of the Hemp Boards

Marking	Ignition Time (s)	Condition After 3.5 min	Surface Burning (%)	Weight Loss after 5 min (%)	Weight Loss after 60 min (%)
PB	72	Burning	55.2	5.83	5.58
A_3	20	Glowing	63.2	14.1	45.6*
B_5	31	Glowing	47.6	8.02	20.4*
C_7	48	Glowing*	47.6	5.88	6.95**
D_9	61	No Glowing	44.0	3.98	3.58
E_11	74	No Glowing	38.4	2.86	2.47
F_13	96	No Glowing	36.6	1.91	1.67

* Effect was noticeable after delicate blowing; ** no signs of glowing

When the density was higher, the time required for the flame to appear on the board surface was longer. However, the ignition time for the reference samples (PB) was longer than that of the hemp fiber board with a similar density (C_7) and was similar to that of the board with a core density higher by 400 kg/m^3 (E_11). After the flame appeared on the surface, the boards differed in their response. The reference fiberboards burned with a bright flame. When the burner was removed, the flame did not extinguish and the reference samples continued to burn. In contrast, for the hemp boards, the flame disappeared spontaneously when a charred layer was formed, with only the fibers in the deeper layers possibly burning. Glowing was observed, which was intensified by stronger air movements. The surface damaged by fire could not be directly related to the board density. Although the area of the burned material was smaller with an increase in the density, the samples from the boards with a low density (A_3 and B_5) burned through and some areas on the other side were also charred. The weight loss after the first inspection period (5 min) was associated exponentially with the hemp board density. Furthermore, the mean weight loss observed for PBs was similar to that in the hemp fiber boards with a similar density. The effect of the hemp board burning after the flame source was removed was clearly observed when the results of the weight loss tests 60 min after the source removal were analyzed. Thus, the boards with a density exceeding 700 kg/m^3 demonstrated a lower weight loss than sample A_3 after 5 min, and this was related to the absorption of water by the dry boards from their ambient environment. In the case of the other boards, the weight loss was significant and was nearly half the weight loss of sample A_3. Despite that fact, it should be concluded that the hemp fiber boards were characterized by better fire resistance properties, as they were not capable of promoting the spread of fire.

CONCLUSIONS

1. The heat transfer coefficient value for the board without veneer (λ = 0.035 W/mK) allowed for this material to be classified as an insulating material. Although the additional layers of veneer noticeably impaired the heat transfer coefficient value, its value was still lower than that for standard wood-based board materials with a similar density.

2. The boards that were produced with hemp fibers, densities ranging from 500 kg/m^3 to 900 kg/m^3, and outer veneer layers were characterized by good noise reduction properties. For these boards, the acoustic insulation factor was higher, not only when compared with that of construction boards with the same density, but also with boards intended to be used as thermal insulation, such as mineral wool or light fiberboards with four times greater thicknesses.
3. The thermal stability of the hemp fibers was only slightly better than that of the birch wood.
4. Although the hemp fiber boards did not burn with an open flame, they did glow, particularly at low densities, and gradually burned out their whole volume. Only boards with a fiber layer density of 900 kg/m^3 were characterized by a fire resistance higher than that of furniture PBs.

REFERENCES CITED

Dukarska, D., Bartkowiak, M., and Stachowiak-Wencek, A. (2015). "White mustard straw as an alternative raw material in the manufacture of particleboards resinated with different amount of urea formaldehyde resin," *Drewno* 58(194), 49-63. DOI: 10.12841/wood.1644-3985.089.04

Dziurka, D., and Mirski, R. (2013). "Lightweight boards from wood and rape straw particles," *Drewno* 56(190), 19-31. DOI: 10.12841/wood.1644-3985.051.02

EN ISO 10140-1 (2010). "Acoustics -- Laboratory measurement of sound insulation of building elements -- Part 1: Application rules for specific products," European Committee for Standardization, Brussels, Belgium.

FAO (2017). "Forest resources of the world," *Food and Agriculture Organization (FAO)*, (http://www.fao.org/docrep/x5345e/x5345e05.htm), Accessed on 4th Nov 2016.

Gava, M., Müzel, S. D., de Lima, L. R., Cortez-Barbosa, J., Garcia, J. N., Ferreira, B. S., Filho, H. J. S., Bernardes, M. S., and De Araujo, V. A. (2015). "Production of particleboards from *Hevea brasiliensis* clones and castor oil-based polyurethane resin," *BioResources* 10(4), 6896-6905. DOI: 10.15376/biores.10.4.6896-6905

He, M.-J., Zhang, J., Li, Z., and Li, M.-L. (2016). "Production and mechanical performance of scrimber composite manufactured from poplar wood for structural applications," *J. Wood Sci.* 62(5), 429-440. DOI: 10.1007/s10086-016-1568-1

Král, P., Klímek, P., Mishra, P. K., Rademacher, P., and Wimmer, R. (2014). "Preparation and characterization of cork layered composite plywood boards," *BioResources* 9(2), 1977-1985. DOI: 10.15376/biores.9.2.1977-1985

Mirski, R., Boruszewski, P., Trociński, A., and Dziurka, D. (2017). "The possibility to use long fibres from fast growing hemp (*Cannabis sativa* L.) for the production of boards for the building and furniture industry," *BioResources* 12(2), 3521-3529. DOI: 10.15376/biores.12.2.3521-3529

Müeller, C., Schwarz, U., and Thole, V. (2012). "Zur Nutzung von Agrar-reststoffen in der Holzwerkstoffindustrie [On the utilization of agricultural residues in the wood-based panel industry]," *Eur. J. Wood Wood Prod.* 70(5), 587-594. DOI: 10.1007/s00107-011-0589-0

Nazerian, M., and Moazami, V. (2015). "Bending strength of sandwich-type particleboard manufactured from giant reed (*Arundo donax*)," *Forest Prod. J.* 65(5-6), 292-300. DOI: 10.13073/FPJ-D-14-00046

Salari, A., Tabarsa, T., Khazaeian, A., and Seraeian, A. (2013). "Improving some of applied properties of oriented strand board (OSB) made from underutilized low quality paulownia (*Paulownia fortunie*) wood employing nano-SiO_2," *Ind. Crop Prod.* 42, 1-9. DOI: 10.1016/j.indcrop.2012.05.010

Shalbafan, A., Tackmann, O., and Welling, J. (2016). "Using of expandable fillers to produce low density particleboard," *Eur. J. Wood Wood Prod.* 74(1), 15-22. DOI: 10.1007/s00107-015-0963-4

Smardzewski, J., Batko, W., Kamisiński, T., Flach, A., Pilch, A., Dziurka, D., Mirski, R., Roszyk E., Majewski M. (2014). "Experimental study of wood acoustic absorption characteristics," *Holzforschung* 68(4), 467-476. DOI: 10.1515/hf-2013-0160

Smardzewski, J., Kamisiński, T., Dziurka, D., Mirski, R., Majewski, A., Flach, A., Pilch, A. (2015). "Sound absorption of wood-based materials," *Holzforschung* 69(4), 431-439. DOI: 10.1515/hf-2014-0114

Sundquist, D., and Bajwa, D. S. (2016). "Dried distillers grains with solubles as a multifunctional filler in low density wood particleboards," *Ind. Crop Prod.* 89, 21-28. DOI: 10.1016/j.indcrop.2016.04.071

Taş, H., and Sevinçli, Y. (2015). "Properties of particleboard produced from red pine (*Pinus brutia*) chips and lavender stems," *BioResources* 10(4), 7865-7876. DOI: 10.15376/biores.11.1.7865-7876

Tittelein, P., Cloutier, A., and Bissonnette, B. (2012). "Design of a low-density wood-cement particleboard for interior wall finish," *Cement Concrete Comp.* 34(2), 218-222. DOI: 10.1016/j.cemconcomp.2011.09.020

Warmbier, K., Wilczyński, A., and Danecki, L. (2013). "Properties of one-layer experimental particleboards from willow (*Salix viminalis*) and industrial wood particles," *Eur. J. Wood Wood Prod.* 71(1), 25-28. DOI: 10.1007/s00107-012-0650-7

Zhang, L., and Hu, Y. (2014). "Novel lignocellulosic hybrid particleboard composites made from rice straws and coir fibers," *Mater. Design* 55, 19-26. DOI: 10.1016/j.matdes.2013.09.066

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