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Experimental Survey of the Sound Absorption Performance of Natural Fibres in Comparison with Conventional Insulating Materials

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Abstract: The purpose of this research is to investigate the acoustic properties of natural fibres and compare them with the values achieved by common insulation materials used in the construction of buildings. Three materials based on biomass were used for testing, namely cork, hemp and fibreboard. From the group of conventional materials, mineral wool, propylat and polyurethane foam were selected. For the purpose of determining the values of the sound absorption coefficient (α), the absorber specimens were tested using the impedance tube and two microphones method, according to standard ISO 10534-2. The measurement was performed for thicknesses of 20, 40, 60, 80 and 100 mm. The highest sound absorption of all materials was measured with a hemp sample at a frequency of 2000 Hz (α = 0.99) and a thickness of 20 mm. The lowest performance was achieved by cork at the same thickness and frequency of 100 Hz (α = 0.02). Among biomass materials, hemp dominated in the entire frequency range and at all thicknesses. The lowest values were for cork, from 160 to 500 Hz with a tendency to exceed the values of the fibreboard sample. Among conventional materials, mineral wool achieved the best results, while the lowest values were recorded for propylat with the occasional exception of the highest frequencies from 1600 to 2500 Hz.

Keywords: natural fibres; impedance tube; ecological building materials; sound absorption coefficient; environmental impact

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1. Introduction

Studies on the use of natural insulating materials for acoustic purposes suggest that many of them have acoustic properties comparable to those of conventional materials, which burden the environment in their life cycle during production, use or disposal. However, the acoustic properties of many natural materials have been insufficiently researched.

At present, the most commonly used acoustic material is various types of polyurethane (PUR) foams. Cradle-to-gate is an assessment of a partial product life cycle, which includes the raw material stage (cradle), the manufacturing stage and the distribution stage (the factory gate before transportation to the customer) [1]. Based on this type of life cycle analysis (LCA), PUR foam has the most harmful impact on the environment among all insulating materials. It is attributed to polyether polyols and isocyanates with the precursor's long chain in the product stage, which includes raw material supply, transport to the manufacturer and manufacturing [2].

In the product stage of rigid PUR foam, global warming potential (GWP) represents 14.8 kg eq./m^2 (with a thickness of 12 cm and a basis weight of 3.96 kg/m^2) [3]. By comparison, if we look at, e.g., 100% ground cork panel, GWP reaches 0.61 kg eq./m^2 (with a thickness of 10 cm and a basis weight of 16.5 kg/m^2) [4].

The use phase is the largest contributor to PUR foam's environmental burden due to the gradual release of the blowing agent used and hydrofluorocarbons (HFCs) during the life of the building. HFCs have a high GWP, which makes a significant contribution to climate change [5].

Natural materials have a low environmental footprint throughout their life cycle. The greatest benefit is 100% recyclability and biodegradability. In addition, waste from the production of other products can be used for the production of acoustic panels. Moreover, many of these materials do not require any additives or binders, as compression moulding is sufficient to compact them. Their advantage is the possibility of processing them into effective 3D models that also satisfy the aesthetic requirements of space [6–9].

One kilogram of hemp consumes approximately 4 kg of CO_2 during growth. At the same time, only 0.2 kg of CO_2 is released into nature. This makes hemp, like other natural plant materials, an important component of nature conservation. This condition is more favourable compared to the CO_2 balance achieved in the production of foamable insulating materials from petroleum or inorganic fibres based on glass or mineral fibres [10]. The amount of primary energy input in hemp insulation is 31.1 MJ/kg. The production of CO_2 is negative, GWP = -0.133 kg CO_2 eq./m^2. The acidification potential or production of SO_2 is in the amount of 0.00539 kg SO_2 eq./m^2 [11–13]. The acoustic characteristics of hemp have been the subject of several studies. The fact that hemp has comparable acoustic properties to glass fibre was proven in [14]. The particle shape factor in relation to hemp and acoustics was also the subject of studies [15–17]. A physical data analysis revealed that acoustic dissipation is governed by the particle pores of the material in the monitored frequency range on the basis of which it is possible to model the acoustic properties of different particle mixes. Studies show that the acoustic behaviour of a material depends on physical parameters such as the shape factor, the porosity, the mean thickness of the particle and apparent particle density.

Natural fibres can be combined with binders, which can also affect acoustic performance. Hemp is often used in combination with concrete in the concept of green buildings. Combining hemp and concrete and comparing different binders for acoustic purposes were studied in [18–21].

From the study on the sound absorption of wood-based materials it can be read that the sound absorption coefficient of cork had higher values than all other woods. Among all tested woods, it was found that cork with an attached tea bag filled with corn fibre was the best selection for sound absorption applications [22]. The possibility of using cork wall panels for room acoustic correction was discussed in [23–25]. Virgin cork as an acoustic absorber was investigated in [26].

The acoustic behaviour of fibreboards with different densities and resin contents was researched in [27,28]. The porosity was the main factor influencing the ability to absorb sound, as samples with a different thickness and resin content showed different porosity. The more porous samples were more acoustically efficient and were also characterized by better thermal conductivity performance. The fact that the sound absorption coefficient of fibreboard increases with a decrease in density was proven in [29].

Noise pollution due to urbanization and industrial development needs to be controlled in an effective way. Different synthetic materials show excellent acoustic performance, but it is necessary to deal with their high cost and environmentally harmful effects [30,31].

The aim of the research was to compare natural and commonly used insulation building materials from the environmental point of view by summarizing the available information on their environmental impacts, and from the acoustic point of view by measurement.

2. Materials and Methods

2.1. Properties and Preparation of Samples

The tested materials were obtained from local suppliers of insulation materials from Slovakia and samples of all materials were cut using water jet technology into smaller pieces of whole boards. Measurement in the impedance tube at the selected frequency range requires circular samples with a diameter of 60 mm. The samples were tested at thicknesses of 20, 40, 60, 80 and 100 mm. The properties of the tested materials from the acoustic and environmental point of view are described in the following subchapters. The samples used for testing are shown in Figure 1.

(**a**) (**b**) (**c**) (**d**) (**e**) (**f**)

Figure 1. Material samples with thicknesses of 20 mm, 40 mm, 60 mm, 80 mm and 100 mm: (**a**) cork, (**b**) hemp, (**c**) fibreboard, (**d**) mineral wool, (**e**) PUR foam, (**f**) propylat.

2.1.1. Cork

The cork oak forests in Portugal are a driving force of sustainable development. Cork bark is harvested every nine years, always between May and August, when the tree is in its most active phase of growth. The bark is harvested without harming the tree, which means that the tree is not cut down [32]. Cork boards are made without the use of foreign binders. At an elevated temperature, through the action of water vapour in combination with high pressure (in an autoclave), the resin is extruded from the cork granules, which compresses the granules into the form of boards. In this way, the boards are produced in the required thickness and density and this process is called "expansion" [33]. In the production process, the use of natural resources is a priority: 93% of energy needs for the production are covered by the use of biomass from the waste of the process itself (cork powder) [34].

The acoustic properties of cork result from its structure and chemical composition. Cork has up to 40 million air cells per 1 cm^3, and 60% of the cork is air. Therefore, cork is characterized by good sound absorption, and it is able to absorb 30–70% of sound in the range from 400 to 4000 Hz. The structure of the cork and its elasticity make it capable of absorbing air and impact sounds and eliminating zones of acoustic bridges [35].

2.1.2. Hemp

Hemp is one of the most environmentally friendly materials. The plant can reach a height of 4500 mm in 120 days. From one hectare it is possible to collect 12 tons of dry raw material, from which 8 tons of material is produced. Rapid growth causes the plants to obscure the soil, preventing it from becoming clogged. As a result, it does not need any herbicides. It contains substances that naturally repel insects, so that no insecticides are needed to protect it. It can be planted and harvested in the same field for several years [33]. Insulation materials based on technical hemp are made of hemp fibre, with the majority of hemp sheath complemented by artificial bicomponent fibres based on polyester which ensure better compactness of the product [36]. Insulation boards also often consist of hemp swarf and hydraulic lime. The blocks are pressed to the required thickness and dimensions and then cured and dried in fresh air without the need for any energy input of heat [37].

Hemp has good sound absorption due to its open pore structure. The long, flexible and tough hemp fibres significantly weaken the intensity of sound waves. This is the basis for the use of hemp insulation as high-quality acoustic insulation and sandwich compositions to increase insulation of airborne sound [38].

2.1.3. Fibreboard

Samples from a single-layer board made of magnesite-bonded wood wool with a fibre width of 1 mm were used for measurement. The board is characterized by its fine-pored natural surface, which has the potential to absorb sound.

The acoustic properties of fibreboards prepared with different densities and resin contents were the subject of a study [39]. Samples with lower density showed a higher sound absorption capacity. Observations confirmed that samples with different densities and resin contents had different porosity levels, and this was the main factor that controlled the ability to reduce noise. The fact that lower fibreboard density results in a higher sound absorption coefficient was also proved in [40].

Acoustic absorption may also depend on the type of wood. The acoustic properties of several types of wood from Europe as well as tropical areas were compared in [41]. The correlation between sound absorption and air permeability of three species of Japanese wood was investigated in [42].

2.1.4. Mineral Wool

The production process of rock mineral wool involves the processing of natural and abundant raw materials (volcanic rock), blast-furnace slag, recycled content (briquettes) and uses fusion and fiberizing techniques. The products obtained come in the form of a "mineral wool mat" consisting of a soft, airy structure. The mat is made of hydrophilic mineral wool, so that it has special parameters unlike standard mineral wool. The facade slabs with longitudinal fibre are suitable for composite external insulation systems, in which they are mechanically fastened with adhesive to a sufficiently cohesive and solid wall surface [43].

Mineral wool insulation is the most effective insulant at reducing sound transmission and reverberations. The fibre matrix with high density and porosity encourages the absorption of sound waves, converting them into heat energy, where other insulation types simply let the sound pass through [44].

However, from an environmental point of view mineral wool as a material poses a recycling problem. While the manufacturing waste is cleaner with a known composition that is commonly reintroduced into the manufacturing process, when disposing of post-consumer waste, the used waste is inappropriately sorted leading to unknown quality and contamination. Most waste rock wool consists of three major components—aluminium oxide (Al_2O_3), silicon dioxide (SiO_2) and calcium oxide (CaO). These contaminants or dirt in the porous rock wool present the biggest hurdle to recycling efforts, making it the most apparent reason behind million tons of waste rock wool piling up every year in landfills and adversely affecting the environment [45]. The issue of waste and recycling of mineral wool as well as new possibilities for its reuse as a filler or as an absorbent for oils is discussed in more detail in [45–47].

2.1.5. PUR Foam

As already mentioned, PUR insulation represents the largest environmental burden of all insulation materials. The impacts on the environment of the production stage are mainly determined by raw material production and processing (GWP = 14.8 kg CO_2 eq./m^2, abiotic depletion potential for fossil resources (ADPF) = 306 MJ/m^2). In all impact categories, upstream processes prior to the production of isocyanate have significant effects, especially in the ozone depletion potential (ODP) = 0.000234 kg CFC-11 eq./m^2. Non-renewable primary energy consumption excluding non-renewable primary energy resources used as raw materials can mainly be attributed to the upstream processes within the production of isocyanate and polyol, approximately 70% in total (226 MJ/m^2). The environmental load in the disposal phase is caused by the combustion of the PUR insulation board (GWP = 8.74 kg CO_2 eq./m^2, ADPF = 2.07 MJ/m^2). All data refer to PUR foam with a thickness of 12 cm and a basis weight of 3.96 kg/m^2 [3].

Due to their open pore structure, density and elasticity, PUR foams are characterized by good sound absorption, especially at high frequencies. Achieving better sound absorption at low frequencies using composite production with bamboo leaf particles has been demonstrated in [48]. Factors that affect the sound absorption coefficient such as thickness, density and flow resistivity have been observed in [49].

2.1.6. Propylat

Propylat is a non-woven fabric made mostly of recycled pieces of textile, which is produced for the purpose of noise reduction in car interiors. The basic raw material is cotton which is hardened by using thermoplastic fibres (polypropylene, polyamide, polyester, polyethylene). Depending on the field of application, propylat is manufactured in densities from 80 to 250 kg/m^3. The particular characteristic of this material is that different densities can be produced within the same component. Thus, it is possible to combine characteristics like sound absorption and rigidity [50].

The influence of bonding methods on the sound absorption characteristic of recycled polyester/cotton nonwoven fabrics was discussed in [51]. The results indicated that recycled cotton and polyester fibrous materials could be effectively used as raw material for sound-absorbing nonwoven fabric at low cost in an eco-friendly manner. The effect of thickness, flow resistance and fibre size on the sound absorption coefficient of nonwovens was investigated in [52].

Given the global problem in the textile industry related to water use and pollution, greenhouse gas emissions and accumulation of waste in landfills, acoustic solutions from waste textiles are considered sustainable and ecological.

2.2. Measuring Setup with the Impedance Tube

For measurements an SW466 impedance tube from manufacturer BSWA TECH was used. The technical parameters of the measuring device are given in Table 1. The complete BSWA TECH SW466 impedance tube system contains [53]:

- Built-in speaker as sound source;
- Sample holders for measuring the sound absorption coefficient;
- Extension tubes for measuring transmission attenuation;
- Microphones and microphone cables;
- Microphone calibrator;
- Hardware for signal generation and data collection;
- Amplifier used to drive the loud speaker;
- Software for analysis and evaluation of measured data.

Technical equipment of the BSWA TECH impedance tube is shown in Figure 2.

Table 1. Technical parameters and equipment of the BSWA TECH impedance tube [53].

Main Measuring Capabilities	Frequency Range	Tube Diameter	Software
Sound absorption coefficient (α) Sound transmission loss (STL)	100–6300 Hz	60 mm	VA-LAB IMP
Microphone calibrator	**Amplifier**	**Hardware**	**Microphones (4)**
model CA115	model PA50	model MC3242	model 1/4″ MPA416

Figure 2. Technical equipment of the BSWA TECH impedance tube: (**a**) microphone calibrator, (**b**) amplifier, (**c**) hardware, (**d**) microphone [53].

The measured parameter was the sound absorption coefficient (α), which can be defined as the ratio of sound energy absorbed by the material to the total impacted energy.

The measurement took place in two frequency bands: 100–800 Hz and 400–2400 Hz, which were combined using software into the resulting frequency band 100–2400 Hz. Each measurement was repeated 5 times to avoid errors.

The system for measuring the sound absorption coefficient (α) for the frequency bands 100–800 Hz and 400–2500 Hz is shown in Figure 3. The system consists of [54]:

- Tube with an inner diameter of 60 mm (60-L);
- Measuring sample holder with an inner diameter of 60 mm (60-S).

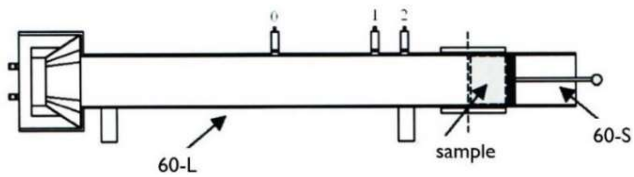

Figure 3. Composition of the measuring system for the sound absorption coefficient (α) (for frequency bands 100–800 Hz and 400–2500 Hz) [54].

The measurement was performed according to the microphone exchange method recommended by the standard to avoid errors. In both frequency bands, the micro-phones exchanged their position six times [55]. The connection of the measuring chain for individ-ual frequency bands is shown in Figures 4 and 5.

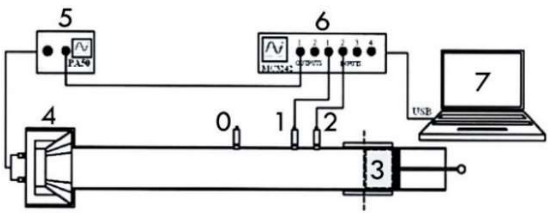

Figure 4. Measuring chain diagram for the sound absorption coefficient in the frequency band 400–2500 Hz: 0—microphone holder; 1, 2—microphones; 3—sample; 4—sound source; 5—amplifier; 6—signal generator; 7—frequency analysis system (software) [54].

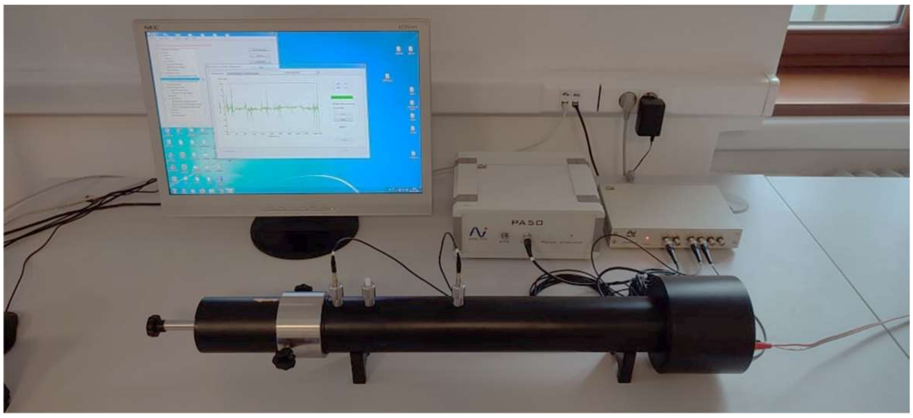

Figure 5. Measuring chain diagram for the sound absorption coefficient in the frequency band 100–800 Hz during real conditions.

2.3. Mathematical Determination of the Sound Absorption Coefficient Using Transfer Function Method (Two-Microphone Method)

In this test method, plane waves are generated in the tube by the noise source. The decomposition of the interference field is achieved by the measurement of acoustic pressures at two fixed locations using wall-mounted microphones, and subsequent calculation of the complex acoustic transfer function H_{12}, the normal incidence absorption and the impedance ratios of the acoustic material (Figure 6) [56].

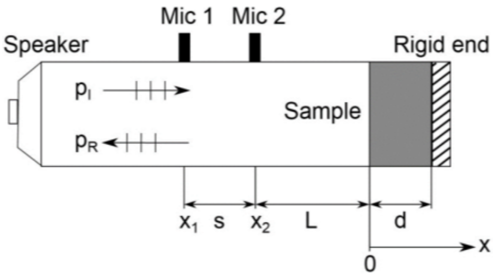

Figure 6. Scheme of impedance tube with two microphones: s—the distance between the two microphones (s = x_1 – x_2); x_1—the distance between the sample and the far microphone location; x_2—the distance between the sample and the near microphone location; p_I—the sound pressure of the incident wave; p_R—the sound pressure of the reflected wave; d—sample thickness [57].

The sound pressures of the incident wave p_I and the reflected wave p_R are, respectively [55]:

$$p_I = \hat{p}_I e^{jk_0 x} \tag{1}$$

and

$$p_R = \hat{p}_R e^{-jk_0 x} \tag{2}$$

where k_0—complex wave number ($k_0 = k_{0'} - jk_{0''}$).

The sound pressures p_1 and p_2 in the two microphone positions are

$$p_1 = \hat{p}_I e^{jk_0 x_1} + \hat{p}_R e^{-jk_0 x_1} \tag{3}$$

and

$$p_2 = \hat{p}_I e^{jk_0 x_2} + \hat{p}_R e^{-jk_0 x_2} \tag{4}$$

The transfer function for the incident wave alone H_I is:

$$H_I = \frac{p_{2I}}{p_{1I}} e^{-jk_0(x_1 - x_2) = e^{-jk_0 S}} \tag{5}$$

Similarly, the transfer function for the reflected wave alone H_R is:

$$H_R = \frac{p_{2R}}{p_{1R}} e^{jk_0(x_1 - x_2) = e^{jk_0 S}} \tag{6}$$

The transfer function H_{12} for the total sound field may now be obtained by using Equations (3) and (4) and noting that $\hat{p}_R = rp_I$, as:

$$H_{12} = \frac{p_2}{p_1} = \frac{e^{jk_0x_2} + re^{-jk_0x_2}}{e^{jk_0x_1} + re^{-jk_0x_1}} \tag{7}$$

Transposing Equation (7) to yield r, and using Equations (5) and (6), one has:

$$r = \frac{H_{12} - H_I}{H_R - H_{12}} e^{2jk_0x_1} \tag{8}$$

The sound reflection factor r at the reference plane (x = 0) can now be determined from the measured transfer functions, the distance between the sample and the far microphone location x_1 and the wave number k_0, which may include the tube attenuation constant $k_{0''}$.

The equation for the normal incidence sound absorption coefficient is:

$$\alpha = 1 - |r|^2 \ [-] \tag{9}$$

3. Results

The sound absorption coefficient is a dimensionless number ranging from 0 to 1. The closer its value is to 1, the more sound the material can absorb. The measured results for a single material in all its thicknesses are shown in Figure 7. Comparisons of results for individual thicknesses and materials are shown in Figures 8–10.

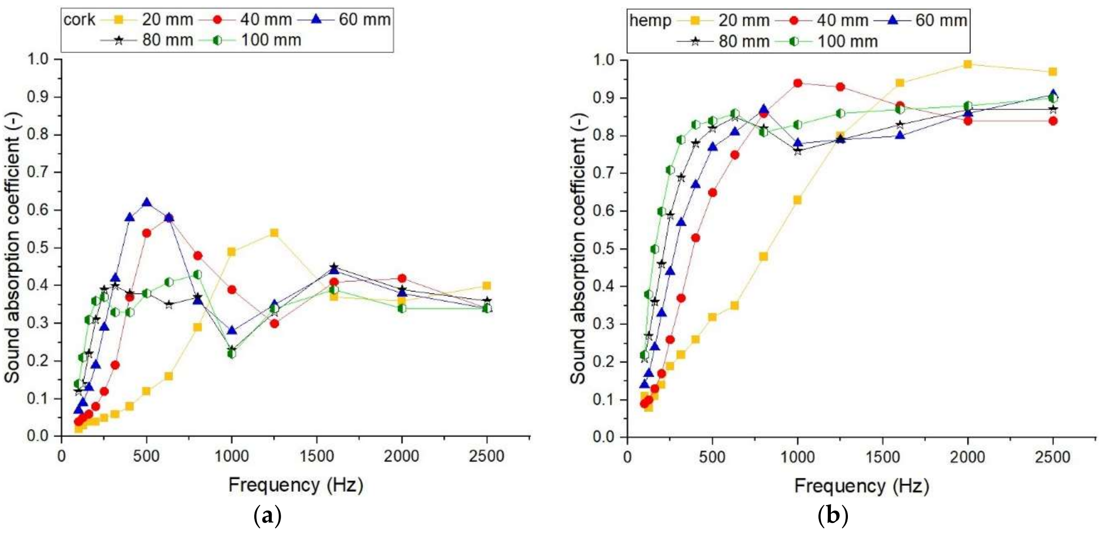

Figure 7. *Cont.*

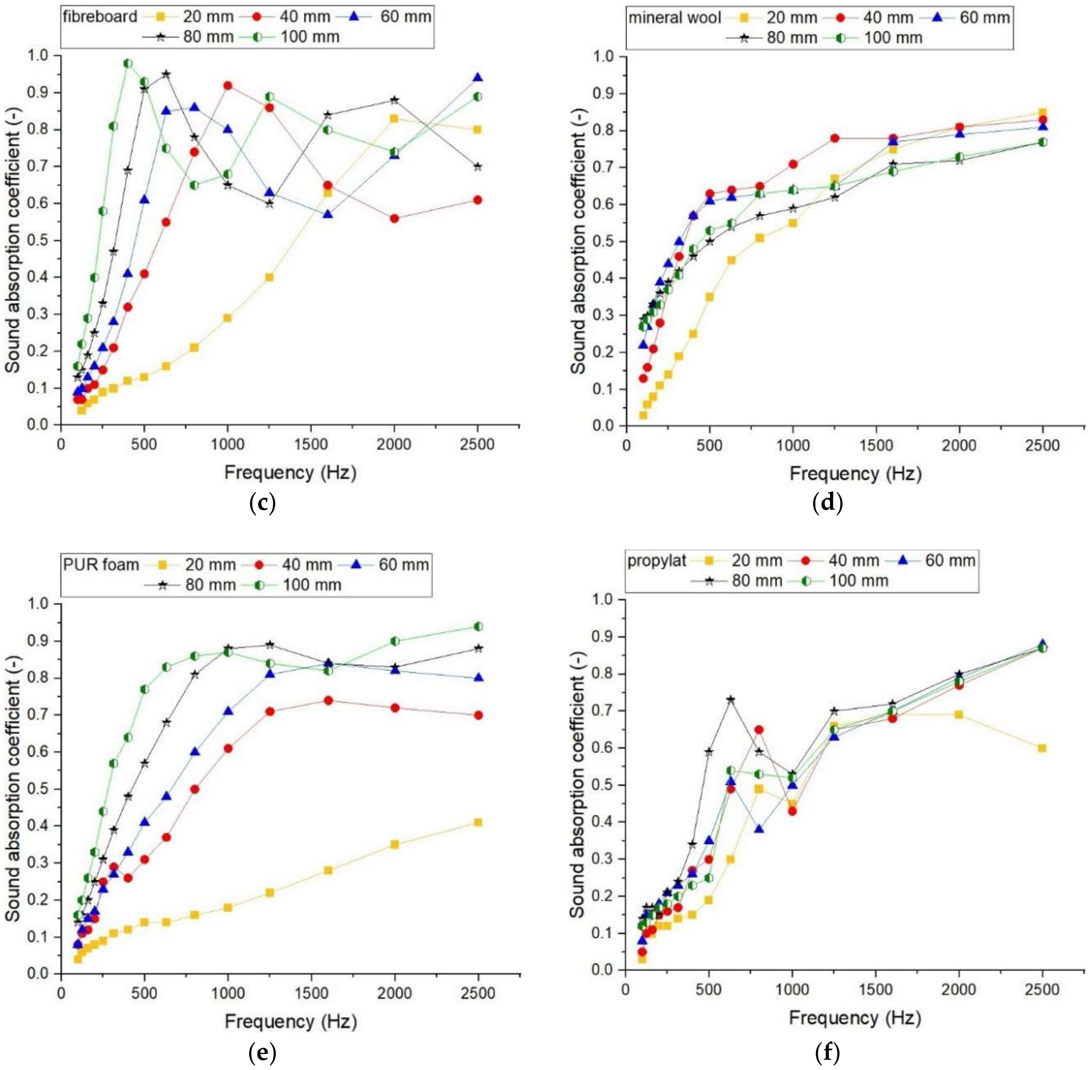

Figure 7. Comparison of sound absorption coefficient of single material with thicknesses of 20 mm, 40 mm, 60 mm, 80 mm and 100 mm for: (**a**) cork, (**b**) hemp, (**c**) fibreboard, (**d**) mineral wool, (**e**) PUR foam, (**f**) propylat.

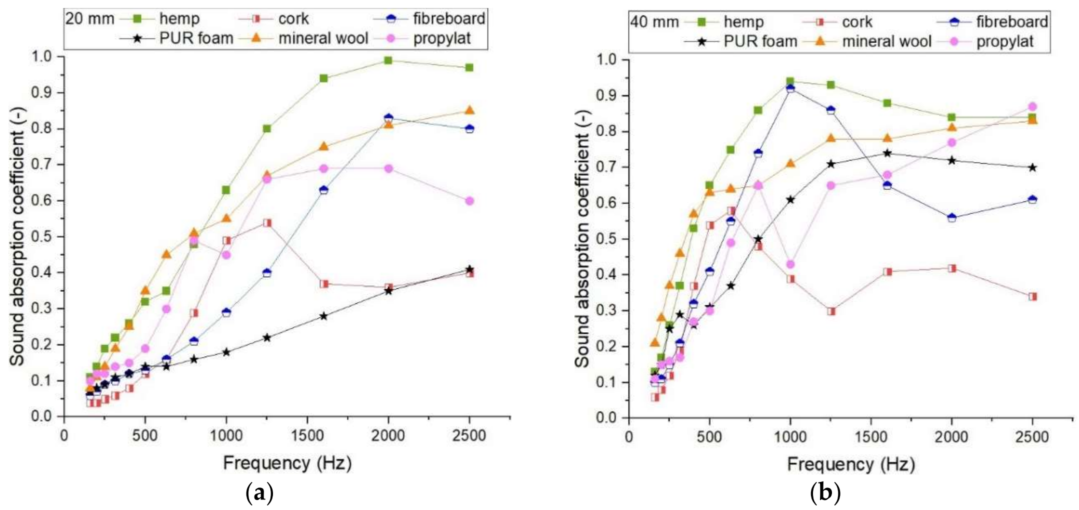

Figure 8. Comparison of sound absorption coefficients for samples of thicknesses: (**a**) 20 mm, (**b**) 40 mm.

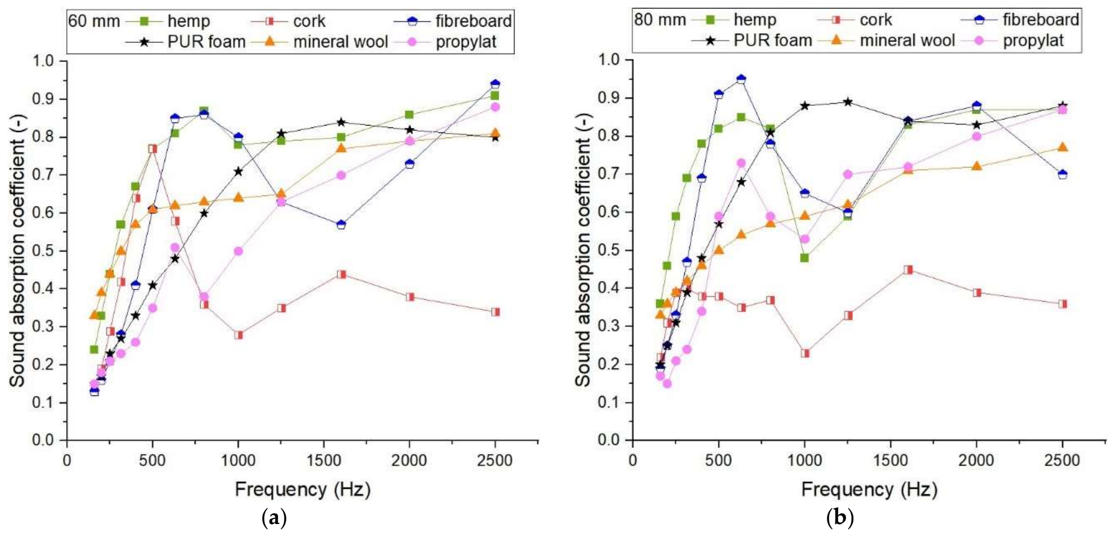

Figure 9. Comparison of sound absorption coefficients for samples of thicknesses: (**a**) 60 mm, (**b**) 80 mm.

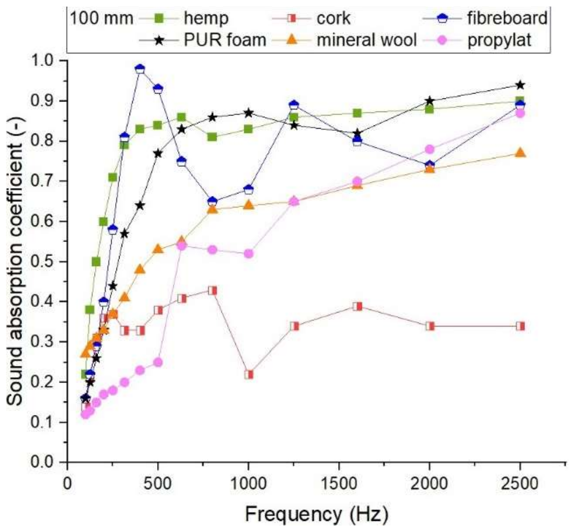

Figure 10. Comparison of sound absorption coefficients for samples of a thickness of 100 mm.

The highest value of materials based on natural fibres was measured for hemp (α = 0.99 (2000 Hz, 20 mm)). Hemp also achieved excellent values at other thicknesses and frequencies: α = 0.97 (2500 Hz, 20 mm), 0.94 (1600 Hz, 20 mm), 0.91 (2500 Hz, 60 mm) and 0.9 (2500 Hz, 100 mm). The fibreboard with values of 0.98 (400 Hz, 100 mm), 0.95 (630 Hz, 80 mm) and 0.94 (2500 Hz, 60 mm) approached the maximum absorption. The maximum for cork was 0.77 (500 Hz, 60 mm).

Among the conventional materials, the best values were recorded for PUR foam, namely 0.94 (2500 Hz, 100 mm), 0.9 (2000 Hz, 100 mm) and 0.89 (1250 Hz, 80 mm). Similar values occurred for propylat: 0.88 (2500 Hz, 60 mm) and 0.87 (2500 Hz, 40 mm/100 mm). The best result for the mineral wool sample was 0.85 (2500 Hz, 100 mm).

From all the materials tested, hemp achieved the highest absorption. In general, the acoustic performance of materials increased with a frequency.

At a thickness of 20 mm, in the case of PUR foam and mineral wool, a rising trend across the overall frequency range can be read from the graph (mineral wool: α = min. 0.03 (100 Hz)—max. 0.85 (2500 Hz); PUR foam: α = min. 0.04 (100 Hz)—max. 0.41 (2500 Hz)). A gradual increase in values with increasing frequency in almost the entire frequency range can also be observed for hemp and fibrewood, with the exception of a decrease at

2500 Hz (hemp: α = min. 0.11 (100 Hz)—max. 0.99 (2000 Hz), α = 0.97 (2500 Hz); fibreboard: α = min. 0.06 (100 Hz)—max. 0.83 (2000 Hz), α = 0.8 (2500 Hz)). The trend of rising, falling and rising (R-F-R trend) was recorded for cork and propylat. The values of the sound absorption coefficient of the cork sample increased up to 1250 Hz, where the highest absorption for the cork was measured (α = min. 0.02 (100 Hz)—max. 0.54 (1250 Hz)). Then the values decreased (1600–2000 Hz) and increased again at 2500 Hz. In the case of propylat, the value decreased at two points, at 1000 (α = min. 0.45) and 2500 Hz (α = min. 0.45), with the highest value being measured at 2000 Hz (α = min. 0.03 (100 Hz), max. 0.7 (2000 Hz)).

In the frequency range 100–400 Hz (α = 0.11–0.26) and 1000–2500 Hz (α = 0.63–0.97), the highest values of the sound absorption coefficient were measured for hemp. At 500–800 Hz in the graph, mineral wool was the leader (α = 0.35–0.51). The lowest values in the frequency band 100–500 Hz were measured for cork (α = 0.02–0.12) and at 630–2500 Hz for PUR foam (α = 0.14–0.41).

It can be stated that at a thickness of 40 mm, the sound absorption of mineral wool increased with the frequency (α = min. 0.13 (100 Hz)—max. 0.83 (2500 Hz)). An increasing trend can also be observed for propylat with a single decrease at 1000 Hz (α = min. 0.05 (100 Hz)—max. 0.87 (2500 Hz), α = 0.43 (1000 Hz)) and for PUR foam with a decrease in the highest frequencies (α = min. 0.08 (1000 Hz)—max. 0.74 (1600 Hz), α = 0.72 (2000 Hz), α = 0.7 (2500 Hz)). The values of the sound absorption coefficient of the hemp sample increased up to the frequency of 1000 Hz, where the maximum was reached (α = min. 0.09 (100 Hz)—max. 0.94 (1000 Hz)), then slowly decreased. The highest value for the fibreboard sample was measured at a frequency of 1250 Hz (α = min. 0.07 (100 Hz)—max. 0.86 (1250 Hz)) followed by a decrease up to a frequency of 2500 Hz, when a slight increase was again recorded. The cork values increased up to 630 Hz, where the highest value for the cork was measured (α = min. 0.04 (100 Hz)—max. 0.58 (630 Hz)), then the values fell (800–1250 Hz), rose (1600–2000 Hz) and fell again (2500 Hz).

The best ability to absorb sound in the frequency range 100–400 Hz was demonstrated by mineral wool (α = 0.13–0.57), and at 500–2500 Hz by hemp (α = 0.13–0.94). At the frequency of 100–250 Hz, the lowest values were measured for cork (α = 0.04–0.12) and at a frequency of 800–2500 cork (α = 0.3–0.48). The lowest sound absorption coefficient at 315 Hz (α = 0.15) and at 500 Hz (α = 0.3) was measured for propylat, and at 400 Hz (α = 0.26) and at 630 Hz (α = 0.37) for PUR foam.

Within a thickness of 60 mm, the sound absorption of mineral wool increased along with the frequency (α = min. 0.22 (100 Hz)—max. 0.81 (2500 Hz)). The values of the PUR foam sound absorption coefficient increased up to a frequency of 1600 Hz, at which the highest value was reached (α = min. 0.08 (100 Hz)—max. 0.84 (1600 Hz)), before decreasing slightly (2000–2500 Hz). The values measured for hemp increased up to a frequency of 800 Hz (α = min. 0.14 (100 Hz)–0.87 (800 Hz)), decreased slightly at a frequency of 1000 Hz (α = 0.78), and from 1250 Hz (α = 0.79) increased again, with the highest value recorded at 2500 Hz (α = max. 0.91). A similar R-F-R trend occurred for fibreboard and propylat. For fibreboard, the sound absorption coefficient increased up to a frequency of 800 Hz (α = min. 0.09 (100 Hz)–0.86 (800 Hz)), decreased at 1000 Hz (α = 0.8), 1250 Hz (α = 0.63) and 1600 Hz (α = 0.57), and increased again at 2000 Hz (α = 0.73) and 2500 Hz (α = max. 0.94). Cork achieved its highest ability to absorb sound at a frequency of 500 Hz (α = min. 0.07 (100 Hz)—max. 0.62 (500 Hz)). As can be seen in the graph after reaching the maximum, the values decreased (800–1000 Hz), increased (1250–1600 Hz) and decreased again (2000–2500 Hz).

The best results in the frequency band 100–250 Hz were measured for mineral wool (α = 0.22–0.44), with the same value at a frequency of 250 Hz (α = 0.44) being shared with hemp. Subsequently, from 315 Hz to 500 Hz, hemp had the highest values (α = 0.57–0.77), which it maintained even at 2000 Hz (α = 0.86) and 2500 Hz (α = 0.91). In the frequency band 630–1000 Hz, wood dominated (α = 0.8–0.86) and in the band 1250–1600 PUR foam (α = 0.81–0.84). Cork performed worst at the lowest frequencies of 100 Hz (α = 0.07) and 125 Hz (α = 0.09), and also at higher frequencies from 800 to 2500 Hz (α = 0.28–0.44). From

160 to 250 Hz the lowest sound absorption capacity was for wood (α = 0.13–0.21), from 315 to 500 Hz for propylat (α = 0.23–0.35) and at a frequency of 630 Hz for PUR foam (α = 0.48).

As with all other thicknesses, at 80 mm the values for mineral wool increased with frequency (α = min. 0.29 (100 Hz)–max. 0.77 (2500 Hz)). The R-F-R trend was observed for PUR foam, hemp and propylat. PUR foam measured its highest value at a frequency of 1250 Hz (α = max. 0.89); from a frequency of 1600 Hz (α = 0.84) to 2000 Hz (α = 0.83) there was a decrease and at the highest frequency of 2500 Hz (α = 0.88) the value again was just below the highest. The minimum value at the lowest frequency of 100 Hz was α = min 0.14. The sound absorption coefficient of the hemp sample increased up to a frequency of 630 Hz (α = min. 0.21 (100 Hz)–0.85 (630 Hz)). The rising trend was interrupted in the frequency range 800–1250 Hz (α = 0.82–0.79) and resumed from 1600–2500 Hz (α = 0.83–max. 0.87). The increase in values for the propylat sample was maintained up to 630 Hz (α = min. 0.14 (100 Hz)–0.73 (630 Hz)), a decrease occurred from 800–1000 Hz (α = 0.59–max. 0.53) and the values again climbed to a maximum of 1250 to 2500 Hz (α = 0.7–max. 0.87). In the case of fibreboard, the values repeatedly increased and decreased, with the highest value at a frequency of 630 Hz (α = min. 0.13 (100 Hz)–max. 0.95 (630 Hz), α = 0.78–0.6 (800–1250 Hz), α = 0.84–0.88 (1600–2000 Hz), α = 0, 7 (2500 Hz)). The values for cork repeatedly increased slightly and decreased several times (α = min. 0.12 (100 Hz), α = max. 0.45 (1600 Hz)). A more significant decrease occurred at 1000 Hz (α = min. 0.23).

In the frequency band 100–125 Hz (α = 0.29–0.3), the highest values were recorded for mineral wool, at 200–400 Hz (α = 0.46–0.78) and at 800 Hz (α = 0.82) for hemp, at 500–630 Hz (α = 0.91–0.95) for fibreboard and at 1000–2500 Hz (α = 0.83–0.89) for PUR foam. At 1600 Hz, the PUR foam and fibreboard shared the same value (α = 0.84). The lowest values were measured for cork in the frequency range 100–125 Hz (α = 0.12–0.14) and 500–2500 Hz (α = 0.23–0.45), and at 160–400 Hz (α = 0.17–0.34) for propylat.

Even at a thickness of 100 mm, the frequency-dependent rising trend of the mineral wool did not change (α = min. 0.27 (100 Hz)—max. 0.77 (2500 Hz)). The rising curve of hemp only decreased slightly at a frequency of 800 Hz (α = min. 0.22 (100 Hz), α = 0.81 (800 Hz), α = max. 0.9 (2500 Hz)). A similar condition can be found for propylat (α = min. 0.12 (100 Hz), α = 0.84–0.82 (1250–1600 Hz), α = max. 0.94 (2500 Hz)) and PUR foam (α = min. 0.16 (100 Hz), α = 0.52 (1000 Hz), α = max. 0.87 (2500 Hz)). The coefficient of sound absorption of wood fibre increased to 400 Hz, where the maximum was measured (α = min. 0.16 (100 Hz)—max. 0.98 (400 Hz)), it gradually decreased from 500 to 800 Hz (α = 0.93–0.65) and from 1000 Hz to 2500 Hz upwards an increase was recorded again (α = 0.68–0.89) with the exception of a decrease in the frequency between 1600 Hz and 2000 Hz (α = 0.8–0.74). The curve of the cork graph alternated with small differences (α = min. 0.14 (100 Hz), α = max. 0.43 (800 Hz)). A more obvious jump from 800 Hz occurred again at a frequency of 1000 Hz (α = 0.22).

Almost absolute absorption was recorded for the fibreboard sample at a frequency of 400 Hz (α = 0.98), which was the highest value overall of all materials at a thickness of 100 mm. By contrast, the lowest power was shown by the propylat sample at a frequency of 100 Hz (α = 0.12).

4. Discussion

It should be noted that the values of the sound absorption coefficient are influenced by the shape, structure and size of the particles as well as the proportion of pores in the material and its bulk density [58,59]. In this case, these aspects were not examined. In general, it is proven that a higher porosity of the material increases its ability to absorb sound, as confirmed by studies devoted to various synthetic and natural materials. Many authors have also concluded that the ability to absorb sound increases with lower bulk density [29,60–63]. The material that in this case achieves the worst performance can provide better performance with targeted improvement of parameters.

Ultimately, therefore, the results apply to the selected samples with specific parameters and cannot be generalized to the type of material. Nevertheless, some natural materials achieve higher absorption than, e.g., with acoustic PUR foam at a greater bulk density; this natural material can therefore be said to have excellent absorption [14,64–66].

The measurements carried out on biomass samples have shown that, similarly to traditional porous materials, these fibres have good sound absorption, mainly at medium and high frequencies. Furthermore, by increasing the material thickness it is possible to obtain significant sound absorption also at low frequencies, when otherwise other ways such as adding air gaps or perforated layer would be needed.

Some manufacturers do not have an environmental product declaration (EPD), so that it is not possible to objectively compare the environmental impacts of all materials. The geographical location, the distance of the transport and other factors also play an important role in the LCA analysis process. For this reason, it is important to extend and harmonise the existing inventory databases of construction materials to the characteristics of the construction industries in each country. To meet this requirement, public institutions should urge manufacturers to have an EPD developed by independent assessors. Without this information, the environmental impact can only be estimated approximately using existing inventories, which in some cases are difficult to adapt to a specific geographical location.

Despite all the stated limits in assessing the environmental impacts of building materials, there is a clear agreement about the high impact of conventional sound absorbers, which require much more industrial processing compared to natural fibres [67].

5. Conclusions

Natural materials have the potential to replace conventional insulating materials because of their good acoustic properties, low price, low weight, availability and last but not least their incomparably lower CO_2 emissions and biodegradability [14,68–70].

From the results of this study, it can be concluded that natural materials can surpass conventional ones even at the thinnest tested thickness. At 20 mm and for the entire frequency band, hemp achieved higher values than PUR foam, and in the frequency bands 100–400 Hz and 1000–2500 Hz it was better than mineral wool. In addition, although the values from 500 to 800 were lower than for mineral wool, the deviations were minimal. Hemp achieved the highest, almost absolute sound absorption of all tested materials at a thickness of 20 mm and a frequency of 2000 Hz ($\alpha = 0.99$). The lowest value was measured at the same thickness for the cork sample at the lowest frequency of 100 Hz ($\alpha = 0.02$).

Out of the natural materials, hemp dominated in all thicknesses and frequency bands. For conventional materials, the highest values occurred alternately for polyurethane foam and mineral wool. At low frequencies, cork performed the least well of the natural materials. Cork was the weakest of the natural materials even at the highest frequencies, with the irregular exception being the middle frequencies at which the values slightly exceeded those for the sample of fibreboard. The lowest sound absorption coefficient among the conventional materials was typical of propylat, at all thicknesses, but values higher than or approaching the values of PUR foam and mineral wool were measured at high frequencies from 1600 to 2500 Hz.

If the material is to serve as part of the internal partitions of buildings, other practical performance criteria must be considered, such as fire resistance, pest resistance, the effect of aging, etc. At present, it is also possible to achieve these properties in the case of natural materials with various surface coatings or additives which do not affect their biodegradability in any way. These criteria could be the subject of further studies as well as a comparison of LCA analyses of individual types of natural materials with conventional representatives such as different types of polyurethane foams and mineral wool. Another aspect of natural materials that may affect their acoustic performance may also be the effect of fibre length and arrangement or the type of binder used.

Materials based on biomass are currently little studied from an acoustic point of view. The measured results can serve as a database for designers who are increasingly emphasizing the use of environmentally friendly materials. Another subject of research will be a prediction model processed into software by means of which it will be possible to determine the sound absorption coefficient at a given frequency without measurement. This software can be used by designers when selecting materials for building walls and partitions, wall, ceiling or hanging tiles, screens, floors, doors or other acoustic elements. The measured values will be used to select the most suitable prediction model for software development based on their comparison with the calculated values.

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