Environmental and Climate Technologies
2024, vol. 28, no. 1, pp. 269–285
https://doi.org/10.2478/rtuect-2024-0022
https://content.sciendo.com

Evaluation and Analysis of Sound Absorption across Various Types of Hemp Fibre

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Received 31.03.2024; accepted 20.05.2024

***Abstract* – Exploring sound absorption solutions, hemp fibre stands out as a compelling replacement for traditional materials like fiberglass, foam, and mineral wool. The aim of this study is to conduct a comprehensive investigation into the sound absorption of six different types of fibre produced from hemp cultivated in the Baltic region. The sound absorption was measured using the impedance tube, transfer function method in accordance with ISO 10534-2 standard. The hemp fibre samples were changed in thickness of 20, 40, 60 mm and density from 50 to 250 kg/m³ in steps of 50 kg/m³. The sound absorption coefficient reaches up to 0.99 at medium and high frequencies. Absorption peaks occur at frequencies of 1000, 1250, 1600, 2500, 3150, 4000, 5000 Hz, depending on the measured fibre thickness, density, and type of measured fibre. It has been determined that in all cases, increasing the thickness of the hemp fibre sample increases sound absorption at lower frequencies. Sound absorption at lower frequencies also generally increases when using denser fibres, but this also depends on the type of hemp fibre being studied. Peaks in the sound absorption coefficient of 0.96-0.99 were mostly achieved when testing fibres with densities of 50, 100, and 150 kg/m³.**

***Keywords* – Hemp; natural fibres; sound absorption coefficient; sound absorbing materials.**

Nomenclature		
BHF	Bleached hemp fibre	–
CHF	Cottonized hemp fibre	–
BCHF	Boiled cottonized hemp fibre	–
DWSHF	Decorticated well stripped hemp fibre	–
DSNCHF	Decorticated short, not combed hemp fibre	–
DSHFH	Decorticated short hemp fibre with 40 % hurds	–

1. INTRODUCTION

In recent years, there has been an increasing focus worldwide on the development of sustainable practices and environmentally friendly alternatives. To ensure sustainability principles, the construction sector is increasingly utilizing eco-friendly materials [1], hence in the field of building acoustics, natural origin materials, waste, or composite materials are often used [2]. In order to improve acoustic comfort, organic, plant-based or waste fibrous materials that effectively absorb sound are often used. For example, Malaysian scientists suggested utilizing

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environmentally friendly materials: coconut fibre and straw [3]. Natural coconut fibre and straw were mixed with synthetic fibre and incorporated into the noise barrier structure. After testing the barrier prototype in anechoic chamber, significant noise level reduction and high acoustic potential of these materials were observed. Zulkifli *et al*. found that coconut fibre can be used as a composite material with a cotton base and perforated panel, resulting in sound absorption increasing up to 0.94–0.95 in the frequency range from 2600 to 2700 Hz [4]. Ouakarrouch *et al*. manufactured and researched eco-friendly composite panels made from 60 % cardboard waste and 40 % natural fibre. Plant fibre was obtained from bamboo, fig tree, palm tree, olive tree, sugar cane stems, wheat straw, and perennial grasses. The sound absorption coefficient ranged from 0.4 to 0.8 at frequency range of 200–1400 Hz [5]. Waste tyre textile fibres also have significant potential as sound-absorbing material [6], [7]. Ružickij *et al*. investigated sustainable acoustic materials made from waste tyre textile fibres (WTTF) and paper sludge (PS), combined with polyvinyl acetate (PVA) as a binder. Sixteen composite panels were developed and tested for their acoustic properties. Scientists found that the most effective combination for sound absorption was found to be 70 % WTTF mixed with 15 % PVA and 15 % water, showcasing significant potential for sustainable development in acoustic material production [7]. Waste tire rubber also has potential in acoustic applications as sound insulation material [8]. Other scientists conducted a preliminary study to explore the possibility of using plastic microfibers for sound absorption applications. The sound absorption values of plastic microfibers in the higher frequency range (above 500 Hz) varied from 0.3 to 0.8, and in the lower frequency range from 0.15 to 0.5 [9]. The growing interest from scientists worldwide in waste or plant-based materials indicates their potential in the field of noise reduction and the need for further research.

Currently, the acoustic properties of hemp fibre products and the potential of this material in acoustics are increasingly being investigated [10]–[12]. Hemp fibre possesses good sound-absorbing qualities due to its porous structure, which includes interconnected pores formed by fibre within cavities and on surfaces. These pores facilitate the absorption of sound waves, allowing them to penetrate the material. Additionally, the viscous effects and heat transfer resulting from energy loss during absorption contribute to hemp fibres sound-absorbing function [13]. According to data provided by researchers, hemp fibre presents a compelling alternative to conventional sound-absorbing materials such as fibreglass, foam, and mineral wool.

Hemp is globally recognized as one of the fastest-growing plants [14]. It offers numerous environmental benefits, from mitigating deforestation [15], [16] to reducing carbon emissions [17], [18]. Hemp has the potential to mitigate deforestation. For example, 0.4 hectares of hemp could produce the same amount of paper as 1.6 to 4 hectares of trees over a 20-year period [15]. Additionally, the usage of hemp materials allows high carbon storage due to CO_2 sequestration during the agricultural phase [17]. The theoretical carbon storage and carbon sequestration potential of hempcrete have been analysed by Arehart *et al*. According to the theoretical model, the total life cycle CO_2 emissions of hempcrete can potentially be negative [18]. Hemp stands out as an exceptionally eco-friendly material. Within just 120 days, this plant can reach heights of up to 4500 mm. From a single hectare, it is feasible to gather 12 tons of dry raw material, yielding 8 tons of usable material. Its rapid growth naturally shades the soil, preventing it from becoming overgrown and eliminating the need for herbicides. Moreover, hemp naturally contains substances that deter insects, making insecticides unnecessary for its protection. What is more, it is possible to cultivate and harvest hemp in the same field for multiple years [19].

The principles outlined in the European Green Deal (EGD) and other European initiatives advocate for the reduction of greenhouse gas emissions, the promotion of circular economy practices, efficient management of natural resources, and the transition from fossil fuels to renewable energy sources. Cultivating hemp contributes to the achievement of the goals set forth in the European Green Deal: hemp fibre absorbs significant amounts of carbon dioxide and exhibits rapid biomass growth. It has the capacity to absorb approximately 10 tons of CO_2 from the atmosphere over a single growing season, thereby enhancing air quality, maintaining thermal balance, and generating positive environmental effects [20]. Due to its ecological potential, hemp fibres are gaining popularity in various sectors including textiles, construction, agriculture, and medicine. In recent years, the cultivation of hemp fibres in the European Union has significantly increased from 19.970 hectares in 2015 to 34.960 hectares in 2019 [21]. Hemp is primarily used to produce hemp fibre and hemp hurds. Although hemp fibres and hurds are well researched globally, scientists emphasize the need for region-specific studies in each area where hemp is cultivated for fibre production. This is because the properties of hemp fibres vary significantly depending on environmental conditions in various cultivation locations [22]. The main factors influencing these differences are climate, soil structure, and precipitation levels. Hemp plants grown in different regions may differ in fibre length and strength. It is observed that the acoustic properties of minimally processed, decorticated hemp fibre are most commonly studied, but attention is not given to other types of hemp fibre used in the textile industry. A comprehensive analysis of different types of hemp fibres would allow for an assessment of the acoustic potential depending on the method of fibre production.

The aim of this study is to conduct a comprehensive investigation into the sound absorption of six different types of fibre produced from hemp cultivated in the Baltic region and to assess the dependency of the results on the thickness and density of the tested samples.

2. Methodology

2.1. Sample Preparation

Six different types of hemp fibre grown in Lithuania were used for experimental research (Fig. 1). The fibre was processed and manufactured at the "Natūralus pluoštas" factory in Kėdainiai.

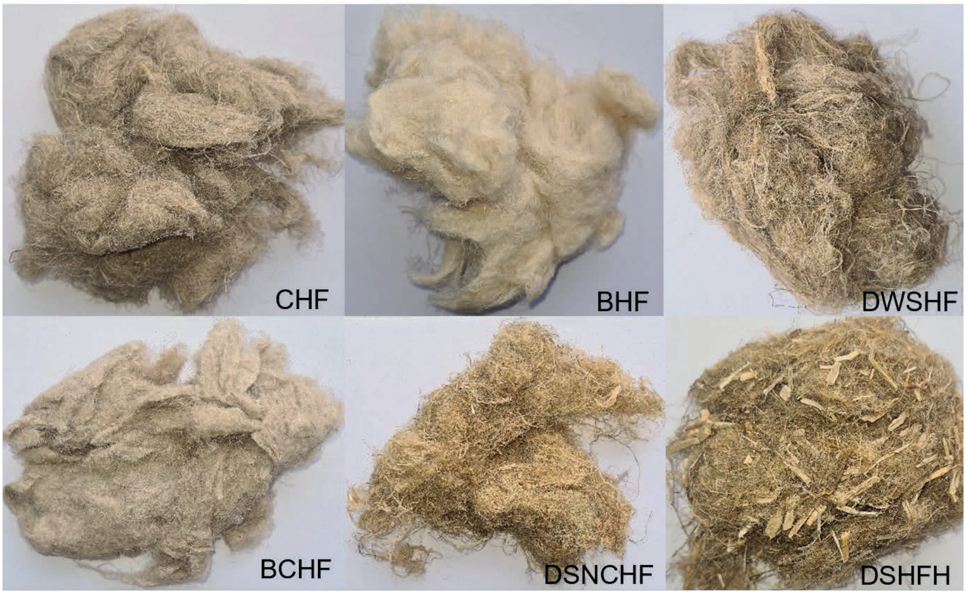

Fig. 1. Types of hemp fibres studied (cottonized h.f., bleached h.f., decorticated h.f. (well stripped), boiled cottonized h.f., decorticated h.f. (short, not combed), f – decorticated short h.f. with 40 % hurds).

The thickness of each tested fibre specimen ranged from 20, 40, to 60 mm, and the density from 50 to 250 kg/m^3 in steps of 50 kg/m^3. The sound absorption properties of these fibres were examined using an impedance tube. The specifications of the tested fibres are provided in Table 1.

TABLE 1. SPECIFICATION OF TESTED FIBRES

Fibre type	Abbreviation	Samples thickness, mm	Samples density, kg/m^3
Bleached hemp fibre	BHF	20, 40, 60	50, 100, 150, 200, 250
Cottonized hemp fibre	CHF	20, 40, 60	50, 100, 150, 200, 250
Boiled cottonized hemp fibre	BCHF	20, 40, 60	50, 100, 150, 200, 250
Decorticated well stripped hemp fibre	DWSHF	20, 40, 60	50, 100, 150, 200, 250
Decorticated short, not combed hemp fibre	DSNCHF	20, 40, 60	50, 100, 150, 200, 250
Decorticated short hemp fibre with 40% hurds	DSHF	20, 40, 60	50, 100, 150, 200, 250

Hemp fibre was placed into plastic forms printed by a 3D printer, which do not influence the research results. The sample holder underwent testing in an impedance tube, confirming that it does not affect the sound absorption measurements. The diameter of the forms is 29.9 mm, and the thickness of the walls is 1.5 mm (Fig. 2).

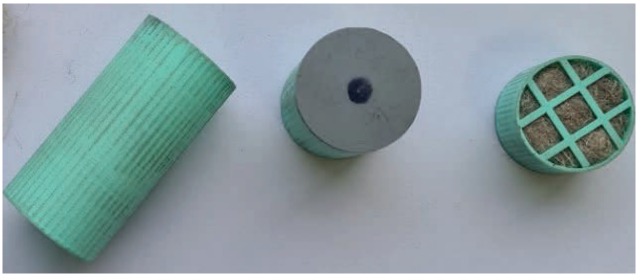

Fig. 2. Fibre sample holder for experimental measurements (from the side, from below, from above).

The material under investigation is weighed and placed into the forms, thus selecting the desired sample density and thickness. This form with fibre inside is later placed into an impedance tube for measurements.

2.2. The Method of Measuring Sound Absorption by Using an Impedance tube

To determine the sound absorption of the materials under investigation, an interferometer is employed (Fig. 3). An interferometer is a device designed for investigating and measuring the sound reflection and absorption of materials. The examination of sound absorption with the interferometer is carried out in accordance with the ISO 10534-2:2023 standard [23].

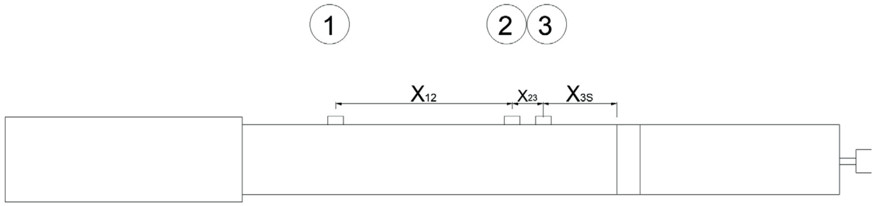

Fig. 3. Scheme illustrating the setup of an impedance tube for conducting experimental sound absorption measurements.

Three microphones, designated as 1, 2, and 3, are positioned at defined intervals from each other. The distance between microphone No. 1 and No. 2, denoted as X_{12}, is set at 100 mm. Likewise, the distance between microphones No. 2 and No. 3, labelled X_{23}, measures 20 mm. The distance between microphone No. 3 and the sample under examination, termed X_{3S}, is established at 60 mm. The diameter of the tube is 30 mm. The minimum and maximum sound level are captured using microphones. The collected data is processed using mathematical-physics formulas and software. After performing the calculations, sound reflection and absorption coefficients are obtained.

The transmission function between the microphones is calculated according to Eq. (1).

$$H_{12} = \frac{p_{2(f)}}{p_{1(f)}}, H_{23} = \frac{p_{a(f)}}{p_{1(f)}}. \tag{1}$$

Knowing the transmission function, the reflection coefficient is calculated:

$$H_{1(160-1000Hz)} = \frac{p_{2I}}{p_{1I}} = e^{-jk_0(x_{12}+x_{23})}; H_{I(1-5kHz)} = \frac{p_{3I}}{p_{2I}} = e^{-jk_0(x_{23})} \tag{2}$$

$$H_{R(160-1000Hz)} = \frac{p_{2R}}{p_{1R}} = e^{jk_0(x_{12}+x_{23})}; H_{R(1-5Hz)} = \frac{p_{3R}}{p_{2R}} = e^{jk_0(x_{23})} \tag{3}$$

Following the calculations made according to Eq. (1)–Eq. (3), the reflection ratio is calculated:

$$R_{(160-1000Hz)} = \frac{H_{12} - H_{I(160-1000Hz)}}{H_{R(160-1000Hz)} - H_{12}} e^{2jk_0(x_{12}+x_{23}+x_{3s})}, \tag{4}$$

$$R_{(1-5kHz)} = \frac{H_{23} - H_{I(1-5\text{kHz})}}{H_{R(1-5\text{kHz})} - H_{13}} e^{2jk_0(x_{23}+x_{3s})}, \tag{5}$$

where R – sound reflection coefficient; k_0 – wave number; j – imaginary number in the complex plane.

Based on the reflection coefficient, the sound absorption coefficient is determined, which is inversely proportional to the reflection coefficient:

$$\alpha = 1 - |R|^2 \tag{6}$$

where α – sound absorption coefficient; R – sound reflection coefficient.

The results are presented in the 1/3 octave frequency range, ranging from 160 to 5000 Hz.

3. RESULTS

Evaluation of 20 mm thick BHF fibre revealed that the samples did not exhibit good sound absorption in the low-frequency range (160–500 Hz), with sound absorption coefficients ranging from 0.07 to 0.27. Analysing the mid-frequencies (630–2000 Hz), the sound absorption ranged from 0.35 to 0.90. The highest sound absorption in the mid-frequency range was observed in the examination of fibre with a density of 150 kg/m^3, reaching up to 0.90 at a frequency of 2000 Hz. Evaluating sound absorption at high frequencies from 2500 to 5000 Hz, it is noted that medium-density fibres exhibit the highest effectiveness. The peak of sound absorption is reached at a frequency of 3150 Hz when using fibre with a density of 100 kg/m^3, where the sound absorption coefficient reaches 0.99 (Fig. 4).

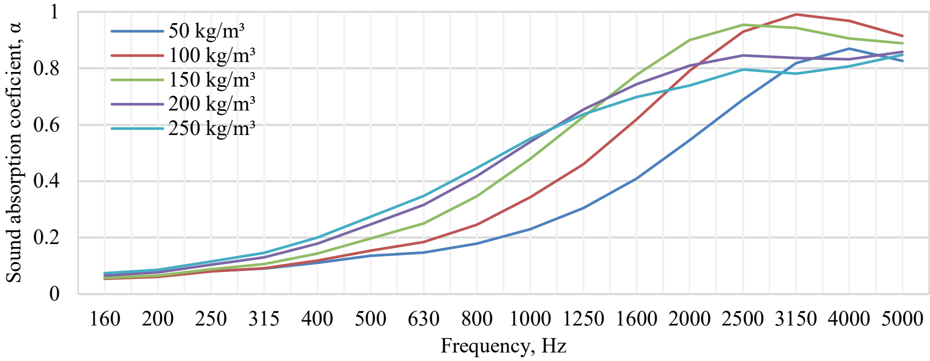

Fig. 4. Results of 20 mm BHF samples.

The sound absorption of 40 mm BHF fibre ranges from 0.10 to 0.54 in the low-frequency range (160–500 Hz), improving with higher density. For mid-frequencies (630–2000 Hz), optimal absorption occurs with 100 and 50 kg/m^3 density fibres, peaking at 1600 Hz with 100 kg/m^3 density reaching 0.99. Poor absorption of high frequencies is seen with 250 and 200 kg/m^3 density fibres, while the 100 kg/m^3 sample peaks again at 5000 Hz with absorption reaching 0.98 (Fig. 5).

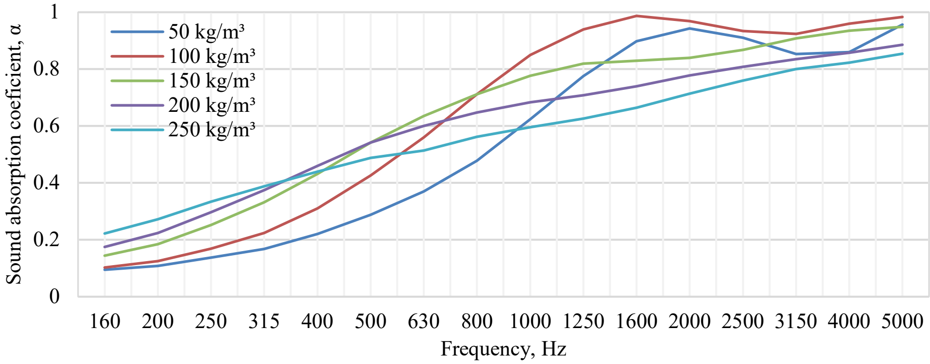

Fig. 5. Results of 40 mm BHF samples.

Analysing 60 mm BHF fibre, highest sound absorption is found at low frequencies (160–500 Hz) with densities of 100 and 150 kg/m^3, ranging from 0.20 to 0.74. Best mid-frequency absorption is seen with 50 kg/m^3 density, peaking at 1250 Hz with 0.98 absorption. For high frequencies (2500–5000 Hz), 50 kg/m^3 density fibres reach up to 0.98 absorption at 4000 Hz (Fig. 6).

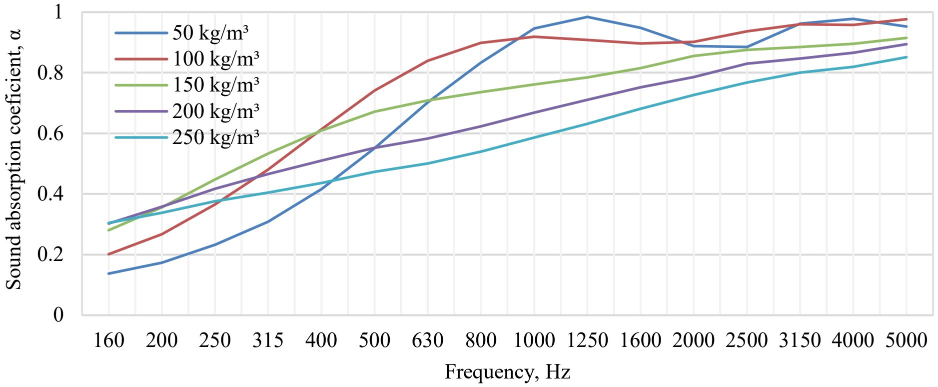

Fig. 6. Results of 60 mm BHF samples.

The 20 mm thick CHF samples showed limited sound absorption in the low-frequency range (160–500 Hz), ranging from 0.07 to 0.28. Mid-range frequencies (630–2000 Hz) exhibited absorption between 0.14 and 0.89. The lowest absorption was seen in 50 kg/m^3 and 100 kg/m^3 density CHF fibres, while the highest absorption occurred in 150 kg/m^3, 200 kg/m^3, and 250 kg/m^3 fibres, ranging from 0.24 to 0.89. The absorption peak was at 3150 Hz with 100 kg/m^3 density fibre, reaching a coefficient of 0.98 (Fig. 7).

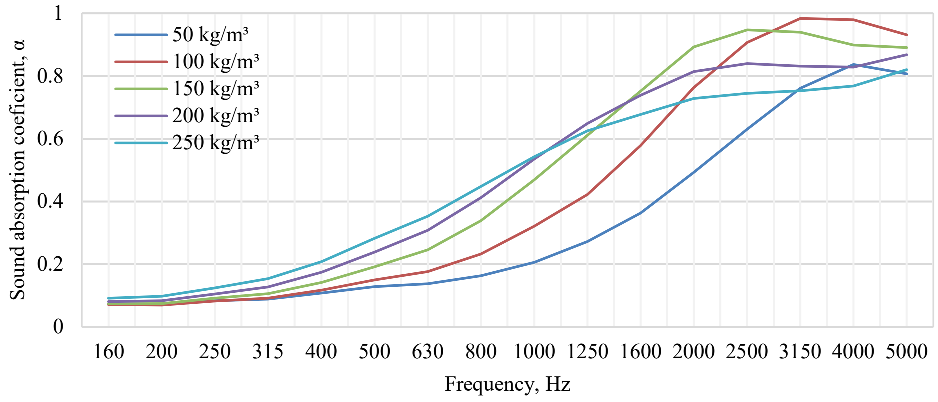

Fig. 7. Results of 20 mm CHF samples.

The 40 mm thick CHF fibre absorbs sound in the low-frequency range (160–500 Hz) from 0.13 to 0.55. Best absorption occurs with densities of 150, 200, and 250 kg/m^3. For mid-frequencies (630–2000 Hz), optimal results are seen with 100 kg/m^3 density, reaching 0.98 at 1600 Hz. High-frequency analysis (2500–5000 Hz) shows absorption from 0.74 to 0.99. Poor absorption is noted with 200 and 250 kg/m^3 density fibres, while 100 kg/m^3 density peaks at 5000 Hz with 0.99 absorption (Fig. 8).

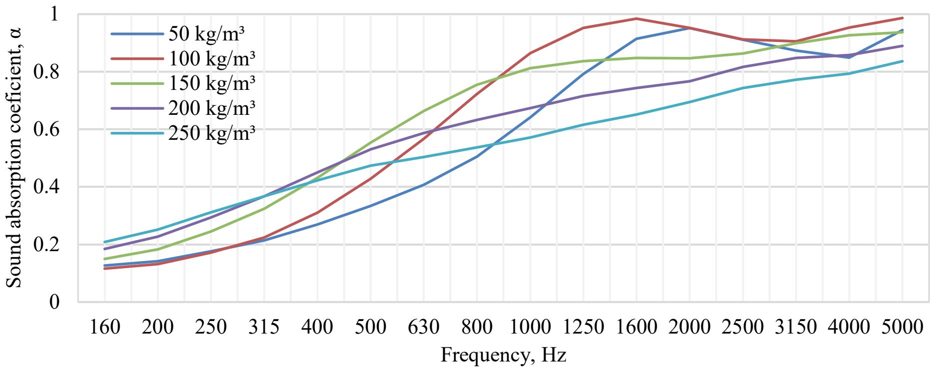

Fig. 8. Results of 40 mm CHF samples.

After examining the 60 mm thick CHF fibre, distinct changes in sound absorption were observed in the low-frequency range according to the density of the samples. The effectiveness of absorbing sound becomes greater with less dense fibre, prevailing from 0.17 to 0.76. The highest sound absorption in the low-frequency range is achieved when testing 100 kg/m^3 density fibre, reaching 0.76 at the 500 Hz frequency. For mid-range frequencies, the best sound absorption results are noticed when testing 50 kg/m^3 density fibre, reaching a peak at 1250 Hz with a coefficient of 0.99. Analysing high frequencies, the 50 kg/m^3 density fibre also reaches 0.99 at the 3150 Hz frequency (Fig. 9).

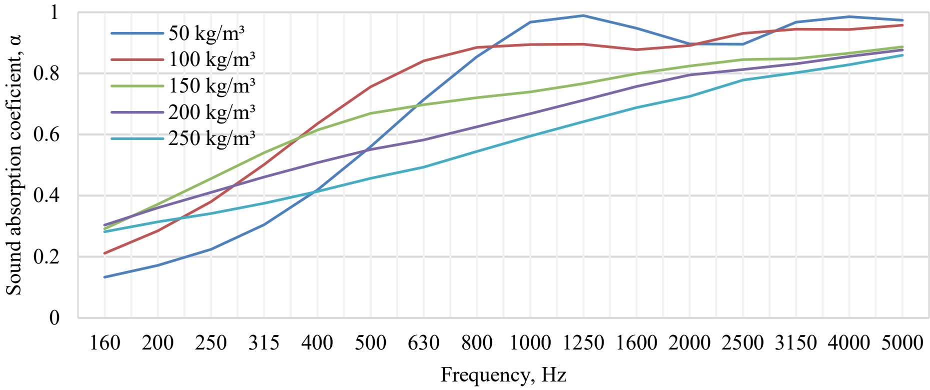

Fig. 9. Results of 60 mm CHF samples.

The sound absorption of BCHF 20 mm thick samples is low at low frequencies. For mid-range frequencies (630–2000 Hz), absorption ranges from 0.17 to 0.89, with the highest absorption seen in 100 kg/m^3 and 150 kg/m^3 density fibres. At high frequencies, the most effective absorption is observed in the lowest density fibres, peaking at 2500 and 3150 Hz with 100 kg/m^3 density fibre reaching 0.95, while 50 kg/m^3 fibre at 4000 Hz reaches 0.97 (Fig. 10).

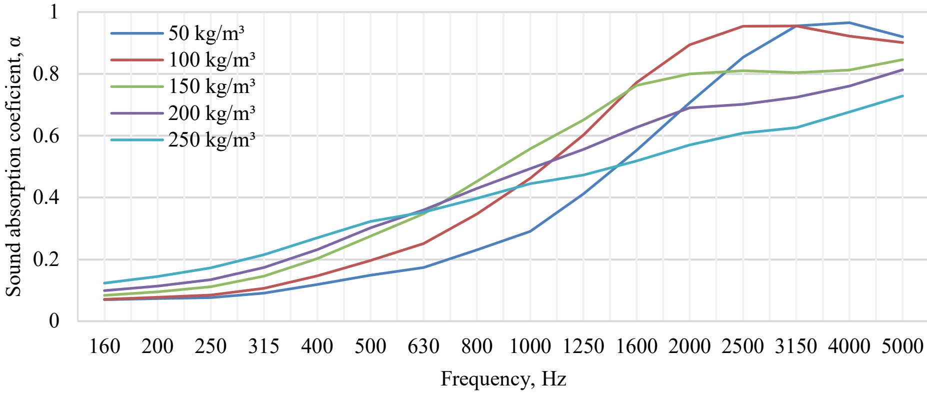

Fig. 10. Results of 20 mm BCHF samples.

In the low-frequency range (160–500 Hz), BCHF 40 mm thick fibre exhibits sound absorption ranging from 0.13 to 0.57. The most effective sound absorption is observed with 50 kg/m^3 density fibre in the mid-range frequencies (630–2000 Hz), reaching a peak of 0.99 at 1600 Hz. High-frequency analysis (2500–5000 Hz) shows sound absorption ranging from 0.61 to 0.99, with optimal absorption again achieved with 50 kg/m^3 density fibre, peaking at 5000 Hz with absorption reaching 0.99 (Fig. 11).

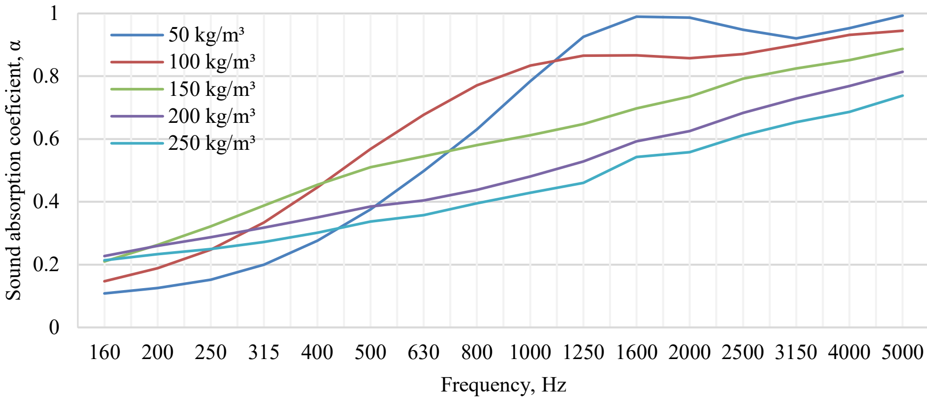

Fig. 11. Results of 40 mm BCHF samples.

Upon testing BCHF 60 mm thick samples, it was found that in the low-frequency range, sound absorption ranges 0.36 to 0.71 for 100 kg/m^3 density. The best absorption, peaking at 0.99, is observed with 50 kg/m^3 density fibre at 1250 Hz in the mid-range frequencies. For high frequencies, absorption ranges from 0.60 to 0.99. At 3150 Hz, the 50 kg/m^3 sample again peaks at 0.99 absorption (Fig. 12).

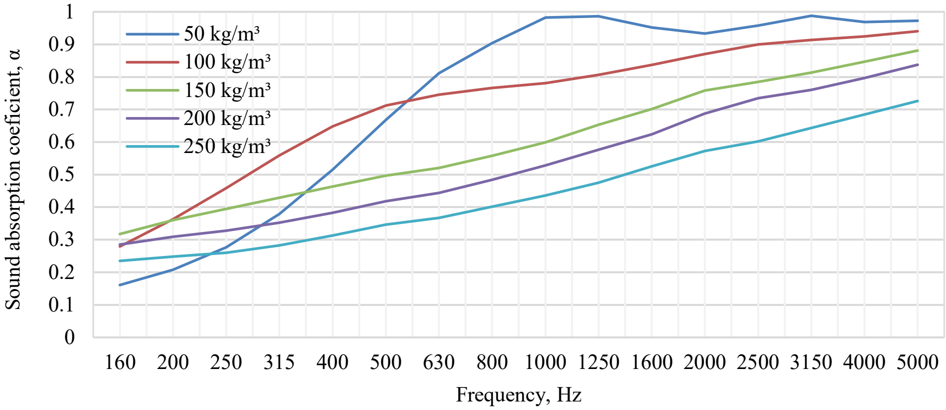

Fig. 12. Results of 60 mm BCHF samples.

After investigating DWSHF 20 mm samples, it was determined that better sound absorption in the low-frequency range is achieved with higher density fibres. In the mid-range frequencies, absorption reaches up to 0.88. The least absorption is observed in 50 kg/m^3 and 100 kg/m^3 density fibres, while the highest absorption is with 200 kg/m^3 and 250 kg/m^3 fibres. At high frequencies, the peak absorption occurs at 3150 Hz with 150 kg/m^3 density fibre, reaching 0.99 (Fig. 13).

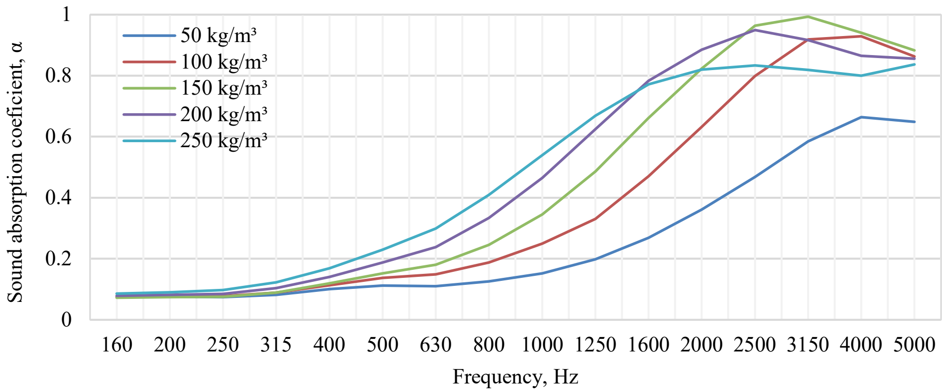

Fig. 13. Results of 20 mm DWSHF samples.

When assessing DWSHF 40 mm thick fibre, it was noted that in the low-frequency range, the sound absorption levels were not particularly high, reaching up to 0.56. In the mid-range frequencies, the best sound absorption results are obtained when testing 100 kg/m^3 and 150 kg/m^3 density DWSHF 40 mm thick fibre. The peak of sound absorption is achieved with 100 kg/m^3 fibre at the 1600 Hz frequency, reaching 0.97. Analysing high frequencies (2500–5000 Hz), sound absorption ranges from 0.74 to 0.99. At the 5000 Hz frequency, the sample of 100 kg/m^3 fibre reaches a second peak, with sound absorption reaching 0.99 (Fig. 14).

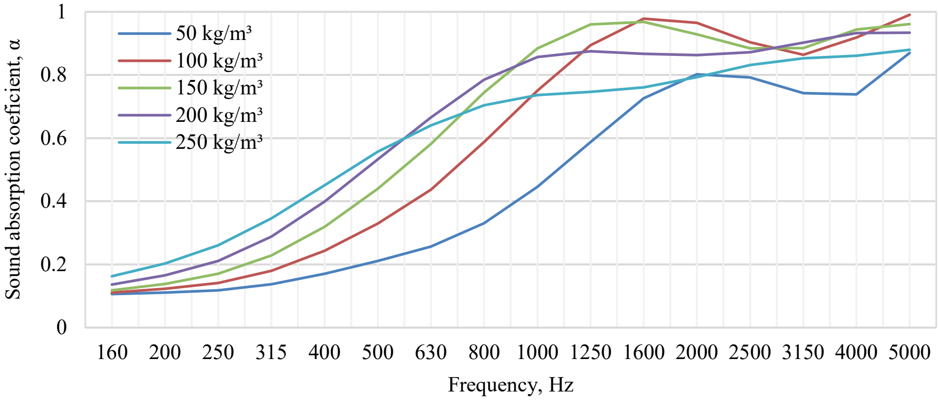

Fig. 14. Results of 40 mm DWSHF samples.

After testing DWSHF 60 mm thick fibre, it was found that in the low-frequency range (160-500 Hz), sound absorption varies from 0.15 to 0.38 for 50 kg/m^3 density and 0.27 to 0.72 for 200 kg/m^3 density. The best mid-range absorption is observed with 100 kg/m^3 density fibre, peaking at 1000 Hz with absorption of 0.99. High-frequency absorption ranges from 0.77 to 0.98, with a second peak at 3150 Hz for the 100 kg/m^3 sample reaching 0.98 (Fig. 15).

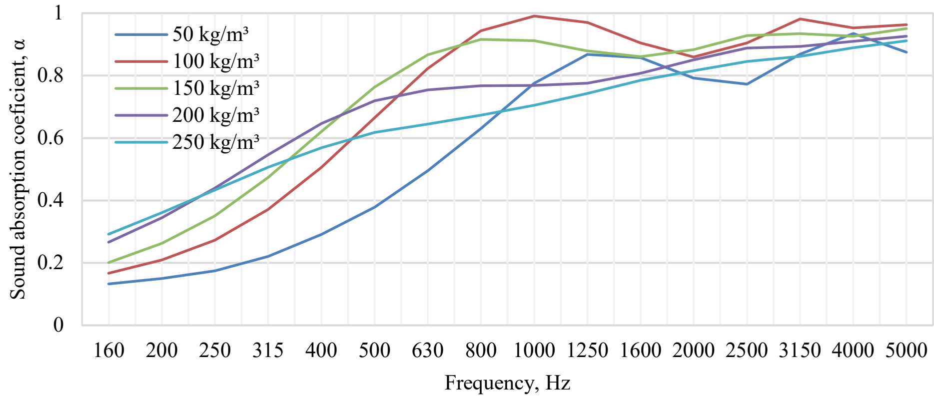

Fig. 15. Results of 60 mm DWSHF samples.

DSNCHF 20 mm thick samples showed limited sound absorption in the low-frequency range (160–500 Hz), ranging from 0.07 to 0.18. In mid-range frequencies (630–2000 Hz), sound absorption is notably dependent on fibre density. Absorption ranges from 0.23 to 0.93 for 250 kg/m^3 density, 0.16 to 0.78 for 200 kg/m^3, 0.14 to 0.61 for 150 kg/m^3, 0.12 to 0.42 for 100 kg/m^3, and 0.08 to 0.26 for 50 kg/m^3 density fibres. The absorption peak is observed at 2500 Hz with 250 kg/m^3 density fibre (0.98), and at 3150 Hz with 200 kg/m^3 density fibre (0.99) (Fig. 16).

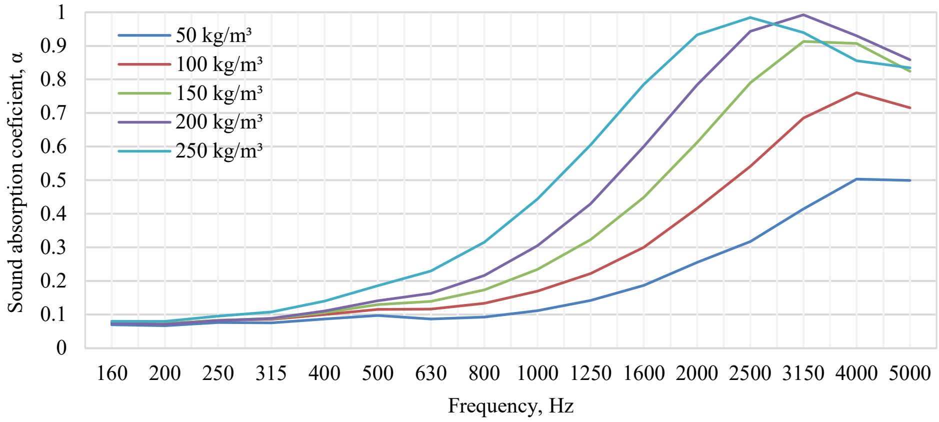

Fig. 16. Results of 20 mm DSNCHF samples.

For DSNCHF 40 mm thick fibre, sound absorption in the low-frequency range ranges from 0.10 to 0.50. In mid-range frequencies (630–2000 Hz), the best sound absorption results are observed when testing 150, 200, and 250 kg/m^3 density fibre. The peak of sound absorption is reached at the 1600 Hz frequency, reaching 0.99 when evaluating 150 kg/m^3 density fibre. Analysing high frequencies (2500–5000 Hz), sound absorption ranges from 0.66 to 0.99 (Fig. 17).

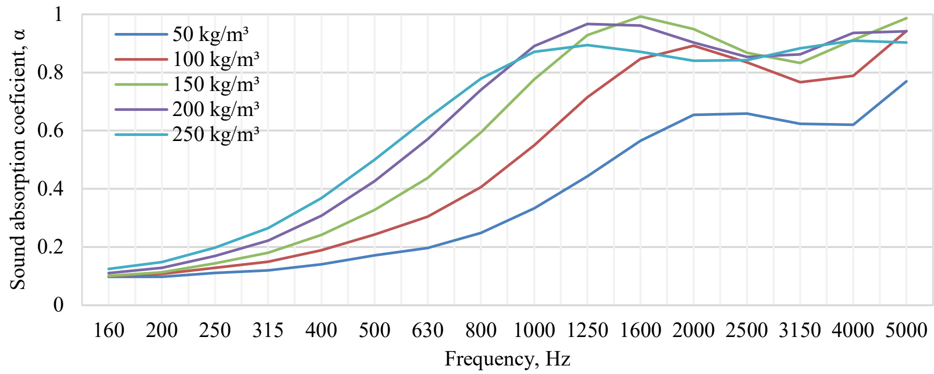

Fig. 17. Results of 40 mm DSNCHF samples.

After investigating DSNCHF 60 mm thick fibre, it was found that the highest sound absorption in the low-frequency range (160–500 Hz) is observed with 200 kg/m^3 and 250 kg/m^3 density fibres, ranging from 0.29 to 0.73. In mid-range frequencies (630–2000 Hz), optimal absorption is achieved with 150 kg/m^3 density fibre, peaking at 1000 Hz with absorption reaching 0.99. At high frequencies (2500–5000 Hz), the absorption coefficient reaches up to 0.9 at 3150 Hz when using 150 kg/m^3 density fibre (Fig. 18).

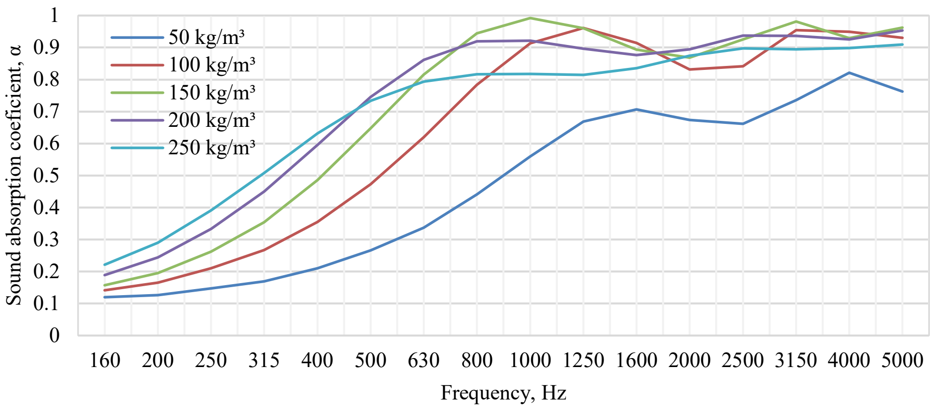

Fig. 18. Results of 60 mm DSNCHF samples.

After examining DSHF 20 mm thick samples, it was noted that in the low-frequency range, higher density fibres demonstrate better sound absorption. Sound absorption in 250 kg/m^3 density samples ranges from 0.10 to 0.27, while for 50 kg/m^3 density fibre, it ranges from 0.08 to 0.10. In mid-range frequencies, sound absorption varies from 0.10 to 0.89. The lowest absorption is observed in 50 kg/m^3 and 100 kg/m^3 density DSHF fibres. The highest sound absorption in the mid-range frequencies is found in 200 kg/m^3 and 250 kg/m^3 fibres, ranging from 0.36 to 0.89. Analysing sound absorption at high frequencies, a similar trend persists, with higher density DSHF fibres exhibiting improved sound absorption. The peak of sound absorption is achieved at 2500 Hz when using 150 kg/m^3 density fibre, with a coefficient of 0.98 (Fig. 19).

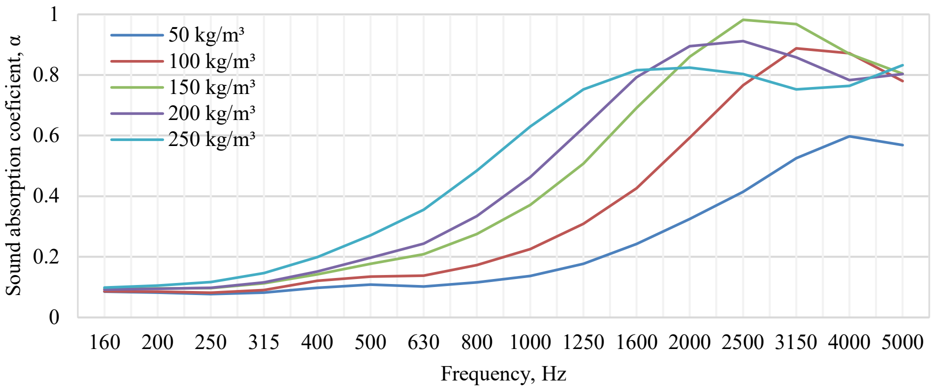

Fig. 19. Results of 20 mm DSHF samples.

When evaluating DSHF 40 mm thick fibre, sound absorption varies across different density samples. In the low-frequency range (160–500 Hz), absorption ranges from 0.10 to 0.53. The best results are seen in mid-range frequencies (630–2000 Hz) with 100 kg/m^3 and 150 kg/m^3 density fibres. A peak absorption of 0.97 is noted at 1250 Hz with 150 kg/m^3 density fibre. At higher frequencies (2500–5000 Hz), absorption ranges from 0.67 to 0.98. A secondary peak is observed at 5000 Hz with a 100 kg/m^3 sample, reaching 0.98 (Fig. 20).

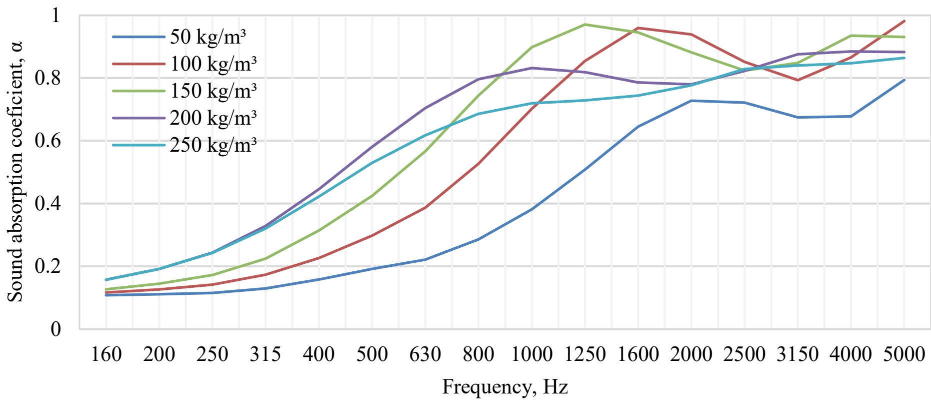

Fig. 20. Results of 40 mm DSHF samples.

Upon assessing DSHF 60 mm thick fibre, it was found that in the low-frequency range (160–500 Hz), absorption varies. For 50 kg/m³ density samples, absorption ranges from 0.13 to 0.32, while for 250 kg/m³ density fibre between 0.32 and 0.59. In mid-range frequencies (630–2000 Hz), the most effective absorption is seen with 100 kg/m³ density DSHF 60 mm thick fibre, peaking at 0.99 at 1000 Hz. High-frequency analysis (2500–5000 Hz) shows absorption between 0.68 and 0.98. At 3150 Hz, a secondary peak of 0.98 absorption is noted with the 100 kg/m³ sample (Fig. 21).

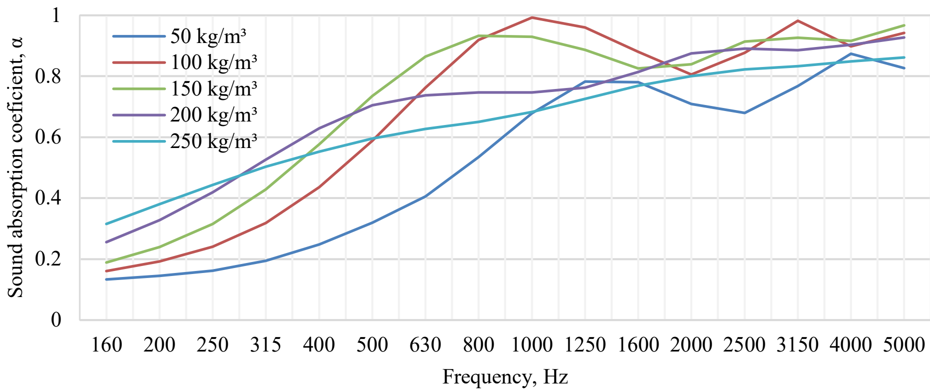

Fig. 21. Results of 60 mm DSHF samples.

4. Discussion

This study has systematically evaluated the sound absorption properties of various hemp fibre types (BHF, CHF, BCHF, DWSHF, DSNCHF, DSHF) with different densities (50–250 kg/m³) and thicknesses (20 mm, 40 mm, 60 mm) across a range of frequencies (160–5000 Hz). The sound absorption values in this frequency range are primarily determined by the sample's thickness, density, and airflow resistivity. At low-frequency range (160–500 Hz) higher density fibres (200–250 kg/m³) demonstrate better sound absorption. As the density of hemp fibres increases, sound absorption in the lower frequencies also increase. For fibrous materials, density is a crucial parameter influencing the sound absorption coefficient. Higher density in fibrous materials means the fibres are more compressed, leading to higher sound absorption coefficient values [24]. This suggests that denser fibres are more effective at absorbing low-frequency sounds, which are typically more challenging to absorb. At mid-frequency range (630–2000 Hz) lower density fibres (50–100 kg/m³) perform optimally, achieving absorption coefficients up to 0.99. This indicates that less dense hemp fibres are more effective for mid-range frequencies. At high-frequency range (2500–5000 Hz) the highest absorption coefficients (up to 0.99) are consistently observed in lower density fibres (50–100 kg/m³), especially at increased thicknesses, demonstrating their effectiveness in managing high-frequency sounds. Increasing the thickness of the fibre samples from 20 mm to 60 mm significantly enhances sound absorption across all frequency ranges, particularly in the low and mid-frequency ranges. When analysing 20 mm samples, the sound absorption peak at higher frequencies is likely due to the sample's insufficient thickness. To shift the peak to lower frequencies, the sample thickness should be at least one-quarter of the wavelength of the target frequency [7]. Thicker fibre samples provide more material to interact with sound waves, thereby improving absorption efficiency. For low-frequency absorption, higher density fibres (200–250 kg/m³) in thicker configurations (60 mm) are recommended. For mid and high-frequency ranges, lower density fibres (50–100 kg/m³) with increased thickness (60 mm) provide the best performance. Similar trends and impacts of density and thickness on sound absorption properties were found by Ruzickij *et al.* when evaluating the sound absorption properties of waste tyre textiles [7], [24], and by Yang *et al.* in their study of the sound absorption properties of natural fibres [25].

This research provides valuable insights for the design and application of sound-absorbing materials made from hemp fibre in various settings, from industrial noise control to architectural acoustics. Based on the obtained results, it has been established that these fibres can be purposefully used, depending on the frequency of sound that needs to be absorbed. Knowing the frequency characteristics of the sound emitted by the noise source, it is possible to select the appropriate type of fibre to absorb that frequency noise. Hemp fibre is a good alternative to conventional sound-absorbing materials due to its porous structure, which effectively absorbs sound waves, coupled with its numerous environmental benefits such as rapid growth and significant carbon sequestration.

5. CONCLUSION

This study has demonstrated that the sound absorption properties of hemp fibres are significantly influenced by their density and thickness. For low-frequency sound absorption, higher density fibres (200–250 kg/m³) in thicker configurations (60 mm) are most effective. In contrast, for mid and high-frequency ranges, lower density fibres (50–100 kg/m³) with increased thickness (60 mm) provide optimal performance, achieving absorption coefficients up to 0.99. The research highlights the versatility of hemp fibres as an environmentally friendly alternative to conventional sound-absorbing materials. Hemp fibrous structure effectively absorbs sound waves, and their rapid growth and significant carbon sequestration offer numerous environmental benefits. By understanding the frequency characteristics of the noise source, it is possible to select the appropriate hemp fibre type to achieve efficient sound absorption, making these fibres suitable for applications in industrial noise control and architectural acoustics. This study provides valuable insights for the design and implementation of hemp fibre-based sound-absorbing materials, paving the way for their use in sustainable acoustic solutions.

To further this research, parameters such as airflow resistivity and fibre size, as examined by SEM, need to be assessed. Future research will aim to better understand and analyse how these parameters influence the sound absorption of the hemp fibres being studied.

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