buildings

MDPI

Article

Experimental Investigation of the Acoustic Performance of a Louvered Hemp Fiber Noise Barrier

Edgaras Strazdas [1,*] and Tomas Januševičius [2]

[1] Department of Environmental Protection and Water Engineering, Vilnius Gediminas Technical University, Sauletekio al. 11, 10223 Vilnius, Lithuania
[2] Research Institute of Environmental Protection, Vilnius Gediminas Technical University, Sauletekio al. 11, 10223 Vilnius, Lithuania; tomas.janusevicius@vilniustech.lt
* Correspondence: edgaras.strazdas@vilniustech.lt

Abstract

Considering the issue of noise generated by equipment that requires high air permeability for operation, a louvered noise barrier was designed. In accordance with sustainability principles, hemp fiber was used in the louvers. The aim of this experimental research was to investigate the effectiveness of the louvered noise barrier in a semi-anechoic chamber and to evaluate the influence of the number of louvers, the angle of inclination of the louvers, and the hemp fiber density on the performance of the barrier. An investigation of the barrier in a semi-anechoic chamber was carried out, using the rotating microphone method. The louvers in the barrier were tilted at angles of 0, 15, 30, or 45 degrees, and the density of fiber used in the different structures was 50, 100, 150, or 200 kg/m^3. The highest insertion loss (IL) of the barrier reached 18.13 dB, and the sound reduction index (R′) reached up to 23.0 dB. The highest determined weighted sound reduction index (R′w) was 14.1 dB, and the equivalent sound level loss (LAeq) reached 9.9 dB (A).

Keywords: louvered noise barrier; acoustic louvers; equipment noise reduction; hemp fiber; sound insertion loss; sound reduction index; anechoic chamber

1. Introduction

The construction and real estate sectors are expanding as urbanization and infrastructure expand, and vacant spaces in cities are increasingly being developed with commercial, industrial, and residential buildings. To ensure comfortable working and living conditions, heating and ventilation systems, heat pumps, and generators are used, which emit noise into the environment. To solve acoustic comfort problems, noise-reducing screens, barriers, and enclosures are often installed; however, high air permeability is necessary to ensure the safe operation of the aforementioned devices, since a large volume of air is discharged into the environment and effective cooling is required. In these cases, typical noise reduction measures are not suitable for noise control. As noise regulation standards become stricter, increasingly more residents and representatives of the industrial and commercial sectors are looking for effective noise control measures.

The European Environment Agency (EEA) 2025 report indicates that, although noise pollution is widely recognized as a major environmental issue, noise still significantly affects the health and quality of life of the population, with more than 112 million Europeans being exposed to harmful noise. Every year, noise is associated with 73,000 premature deaths and 49,000 cases of cardiovascular disease, and as many as 16.9 million people

Check for updates

Academic Editor: Salvatore Verre

Received: 3 May 2026
Revised: 15 June 2026
Accepted: 20 June 2026
Published: 23 June 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

experience severe annoyance and sleep disorders. Noise also affects children's development, learning, and behavior [1,2]. Although noise from road and air transport remains the main source, industrial and residential noise sources in urban areas, workplaces, and residential environments cause similar problems. Heating, Ventilation, and Air-Conditioning (HVAC) systems (which comprise ventilators, fans, heat pumps, and air ducts) [3], as well as generators and compressors, are common sources of noise in residential and industrial environments. The noise generated by this equipment—like that from the previously mentioned noise sources—can cause problems for residents due to sleep disruption and annoyance, which can lead to more serious health problems [3,4]. Although air-source heat pumps are considered a key technology for reducing carbon dioxide emissions associated with building heating and have become a viable alternative to conventional fossil-fuel-fired heating systems, their rapid deployment exacerbates the problems related to the noise emitted by these devices in the living environment. Previous studies have demonstrated that subjective responses to air-source heat pump noise are influenced not only by sound pressure levels but also by psychoacoustic characteristics such as loudness, roughness, and tonality, which are primary psychoacoustic predictors of annoyance, arousal, and valence [5]. It is worth noting that in recent years, more attention has been paid to the impacts of noise generated by heat pumps on people, with noise emissions being one of the main obstacles to the wider deployment of heat pumps. Studies have shown that when assessing air-source heat pump noise, it is important to take into account not only the sound pressure level but also the acoustic characteristics and background noise conditions. In general, there is a great need to develop effective noise reduction measures and optimize installation solutions for these devices [6].

HVAC systems are essential for maintaining comfortable indoor environments. Although they regulate temperature and improve indoor air quality, these systems can generate significant noise, which may negatively affect occupants. HVAC noise is recognized as a stressor that adversely affects sleep, cognitive performance, and learning. Prolonged exposure to such noise can lead to stress, sleep disorders, and cognitive decline. Scientists have emphasized that noise control measures should be integrated into the HVAC system design process from the early stages; for example, by optimizing the equipment layout, ductwork systems, and sound absorption solutions [3]. HVAC system noise is typically dominated by low-frequency content, which is caused by vibrations from mechanical and electrical system components, inadequate vibration isolation, and incorrect installation. These vibrations are transmitted through building structures and felt by occupants, potentially causing annoyance. In these systems, most low-frequency noise—in the frequency range from 16 to 250 Hz—is caused by fan operation, most noise in the mid-frequency range (250–500 Hz) is caused by dampers, and most noise in the high-frequency range (typically 500–8000 Hz, but also extending up to 20,000 Hz) is caused by diffusers [3,7]. Meanwhile, noise generated by generators is attributed to the operation of their exhaust pipe, AVR panel, and radiator. Noise generated by generators at high frequencies (2000–8000 Hz) is associated with internal combustion processes, while that at low frequencies (<250 Hz) originates from the mechanical vibrations of the structure and radiator. On average, noise generated by generators consists of 60% high-frequency energy and 40% low-frequency energy. Overall, generator noise affects auditory and cognitive functions, causes stress, and disrupts concentration. The equivalent noise level generated by generators can reach up to 100 dB at the source [8]. Although household generators emit an average noise level of ~74 dB, they can also reach >100 dB, thus significantly exceeding recommended limits [9,10].

Commonly used HVAC noise control measures include acoustic screens, sound-absorbing materials, and noise barriers. The implementation of effective control measures,

such as vibration isolation, active noise control, damping, and architectural modifications, is essential to reduce noise transmission. The installation of noise barriers near HVAC outdoor units can significantly reduce sound levels—often by several decibels [3]. Nevertheless, there is still a lack of studies systematically assessing the influence of the geometry of ventilated louvered noise barriers on their noise reduction performance. Previous studies have shown that the noise reduction efficiency of a barrier is significantly determined by its geometry, height, and distance from the noise source. Properly designed acoustic barriers can significantly reduce the noise emitted by heat pumps in residential environments [11]. Studies have shown that acoustic screens and protective structures can reduce sound pressure levels by several decibels without reducing the ventilation efficiency of heat pump equipment, and the Danish Energy Agency recommends installing barriers that can reduce noise in the surrounding environment by at least 5–10 dB [12].

Noise barriers with high air permeability are increasingly being studied by scientists. To achieve greater air permeability or proper shading, scientists have proposed several types of barriers, including sonic crystals or louvered structures [13]. Sonic crystals have been found by scientists to enable sound attenuation from 16 to 25 dB (A) [13]. Louvered structures are often used as building facade elements or structural elements. They ensure the necessary light and air permeability, while also having sound-absorbing properties [14]. Noise-attenuating louvers can be used to reduce noise from engineering equipment or road noise [15], and have been described in a patent [16] published on 1 December 1992 regarding reduce the noise generated by stationary noise sources that require ventilation or air intake or exhaust. As such devices cannot be fully covered with sound-attenuating structures, structures that allow air to pass through while reducing noise transmission are necessary.

The first evaluation of louvers for noise reduction was conducted by the authors of [17], who investigated the effectiveness of a noise reduction structure with a single- or double-louvered structure. The sound reduction efficiency of these structures was found to be 12 and 21 dB, respectively [17]. Research procedures and their effectiveness have been evaluated in [18], where the structure under study consisted of perforated metal plates with an absorbing layer between them. The sound attenuation properties of acoustic louvers were studied using the impulse response method and it was found that at low frequencies, sound transmission is mainly determined by the mass of the louver structure and does not depend on the angle of inclination of the louvers. At medium and high frequencies, factors such as diffraction, interference, and absorption become significant, leading to the dependence of sound attenuation performance on the inclination of the louvers. Overall, it was found that the geometry of the louvers has a minimal effect on low-frequency sound attenuation, while their mass has little effect at higher frequencies [18]. An active noise reduction system integrated into a louver structure was proposed in [19]. It was found that when installing piezoelectric sensors in the louvers that absorb low-frequency sound, the total sound loss reached up to 30 dB and was 10 dB higher in the low-frequency range, when compared with the passive noise reduction system in the louvers [19]. Other researchers have evaluated the effectiveness of louvers integrated into building facades or window elements in reducing sound [14,20]. For example, Lee found that the sound reduction efficiency of a double facade with a louver structure made of polycarbonate sheets ranged from 3 to 6 dB (A) in the frequency range from 500 to 4000 Hz [20]. In [21], three louver configurations were investigated: louvers made from metal plates, louvers covered with 20 mm-thick polystyrene foam panels on both sides, and louvers covered with 15 mm-thick glass wool panels. According to the test results, the best noise reduction characteristics were obtained with the glass wool panel louvers, for which the sound insulation index ranged from 10.8 to 12.5 dB [21]. The authors of [15] studied a louvered noise barrier

for traffic noise reduction through experimental testing in a sound attenuation chamber. Experimental studies were conducted using different louvered barrier configurations, characterized by different louver tilt angles and varying thicknesses of the sound-absorbing material [15]. The sound attenuation was highest in the 2500 and 3150 Hz octave frequency bands. Depending on the angle of inclination of the louvered barrier, the sound attenuation in the mentioned frequency bands reached up to 28 dB (A), and the equivalent sound pressure level was reduced to 17 dB (A). The best sound attenuation performance was achieved using 30 mm-thick mineral wool [15].

Despite these developments, several important knowledge gaps remain. Previous studies have mainly focused on louvered barriers incorporating conventional sound-absorbing materials such as mineral wool, glass wool, and rubber-based materials. Although the influence of louver geometry has been partially investigated, the combined effects of the louver inclination angle, number of louvers, and hemp fiber density on the acoustic performance of ventilated louvered noise barriers have not yet been systematically evaluated. In the studies reviewed above, all investigated louvered noise barriers were based on metal sheet structures combined with various sound-absorbing materials. However, to date, no study has reported a louvered noise barrier composed of perforated louvered panels with hemp fiber as the internal sound-absorbing material. In general, the application of hemp fiber as a sustainable sound-absorbing material in louvered noise barriers intended for HVAC equipment, heat pumps, and generators remains largely unexplored.

In the studies described above, porous granular or fibrous materials were most often used as sound-absorbing materials in louvers, such as various types of rubber granulate, as well as glass and mineral fiber. These sound-absorbing porous materials are often used in combination with perforated plates made of materials such as steel, glass, and plastic. The perforation of a sound-absorbing plate can influence the effectiveness of the material in absorbing sound at various frequencies. The main parameters affecting sound absorption efficiency are the perforation size, shape, area ratio, and arrangement, as well as the thickness of the perforated plate and the air gap between the plate and the sound-absorbing material. Perforated plates usually absorb medium- and high-frequency sounds more effectively. To effectively absorb low-frequency sound, perforations with larger diameter, deeper air gaps, or additional sound-absorbing materials are used. Perforation increases sound absorption as the viscous and thermal losses of the sound wave increase as it interacts with the edges of the perforations. Although round perforations are typically used in louvered barriers, other shapes can also be used, such as square, triangular, or elongated perforations. The shape affects the propagation of sound waves through the perforated surface and, accordingly, the sound absorption characteristics. Another important aspect is the perforation density (or perforation coefficient), which refers to the fraction of perforated surface area on the panel. A higher perforation density usually increases sound absorption because more sound waves can interact with the holes. Furthermore, the thickness of the perforated panel and the air gap between the sound-absorbing material and the perforated panel affect the range of frequencies that can be absorbed. Thicker panels and a larger air gap allow for more efficient absorption of lower frequencies. Additional layers of sound-absorbing material behind the perforated panel can significantly improve the sound absorption performance, and the air cavity between the panel and the sound-absorbing material can act as a Helmholtz resonator, which can be tuned to specific frequencies depending on the dimensions and perforations of the cavity [22].

As mentioned earlier, in louvered noise-reducing structures, porous granular or fibrous materials are most often used as fillers, including rubber granules, glass wool, and mineral wool. Sustainable, environmentally friendly materials are increasingly being studied in the field of acoustics. For example, the authors of [23] indicated that natural and

recycled fibers can serve as a sustainable alternative to traditional acoustic materials due to their good sound absorption properties and lower environmental impact, while those of [24] demonstrated that natural fibers such as hemp, kenaf, cork, and sheep wool exhibit promising sound absorption characteristics and can be effectively used in acoustic applications. More recently, the authors of [25] showed that acoustic structures based on natural fibers can effectively absorb sound over a wide frequency range. Furthermore, the authors of [26] reported that plant-based materials can achieve high sound absorption performance and thus represent viable solutions for sustainable noise control. One of the most ecologically attractive alternatives to conventional sound-absorbing or insulating materials, which meets the principles of the European Green Deal and sustainability, is hemp fiber [27–30]. Hemp plants are characterized by rapid biomass growth [28], and growing hemp plants reduces the amount of carbon dioxide in the atmosphere [29,30]; in particular, the cultivation of 1 hectare of hemp plants allows for the absorption of about 10 tons of CO_2 from the atmosphere during one growing season [27]. Hemp plants are characterized by high resistance to various pests and can be cultivated repeatedly on the same land, as they do not deplete the soil [31]. Due to these ecological advantages, hemp plant cultivation has been increasingly expanding in Europe, growing from 20,540 hectares in 2015 to 33,020 hectares in 2022 [32]. Hemp fiber has good sound absorption properties and, by densifying the fiber, sufficient sound insulation properties can be achieved [33–40]. In addition to acoustic applications, hemp fiber is increasingly being incorporated into sustainable construction materials, including cement-based composites and geopolymer systems, due to its low environmental impact and favorable physical and mechanical properties. Recent studies have demonstrated that hemp fiber can contribute to improved thermal insulation performance, reduced material density, and enhanced sustainability of building materials, further supporting its growing use in green engineering applications [41,42]. However, although hemp fiber has great environmental potential and sustainable material properties, as well as good acoustic properties, it is worth noting that it is a biodegradable material that absorbs moisture and decomposes over time; therefore, when using it in noise-reducing structures, preventive measures must be implemented to ensure its long-term durability. When planning to use the barrier in outdoor conditions, to improve the outdoor durability of hemp fiber-based materials, their water and moisture, weathering, and biotic resistance should be evaluated. To improve these parameters, methods such as alkali, silane, chemical impregnation, salicylic acid, or natural monoterpene phenols treatments could be considered [43–45].

Before conducting this research, extensive experimental studies for the evaluation of different hemp fibers were carried out, confirming the possibility of using hemp fiber in the studied structure. After evaluating these preliminary results, bleached hemp fiber (BHF) was selected, which showed the highest sound absorption and transmission loss results when incorporated in the material. When testing samples with a thickness of 60 mm and a density of 250 kg/m^3, the sound absorption coefficient of bleached hemp fiber in the medium- and high-frequency ranges reached up to 0.99 and the sound transmission loss (DTL) reached up to 58.64 dB [40].

The aim of this experimental study was to investigate the effectiveness of a louvered noise barrier in a semi-anechoic noise reduction chamber and to evaluate the influence of the number of louvers, louver inclination angle, and hemp fiber density on the performance of the barrier.

It should be noted that this is a continuation of research previously conducted with other structures using a similar methodology. Based on the results and experience gained from these previous studies, a metal louvered noise barrier was designed and manufactured, the design of which is described and studied in this article. The structure uses hemp fiber

selected through the experimental studies mentioned above [40]. For comparison, a louver barrier filled with a mixture of rubber granulate plates and loose rubber granulate was also manufactured. The results obtained using this comparative material have been presented at the international conference Forum Acusticum Euronoise 2025 [46].

2. Materials and Methods

2.1. Development and Design of a Louvered Noise Barrier

The main objectives of this study were to design and manufacture a louvered noise barrier, and to evaluate the performance of the prototype using experimental laboratory methods in a noise-reducing chamber. The prototype louvered noise barrier was designed to fully reflect the proposed concept and to be easily scalable into a full-scale product.

The filler material used in the louvered noise barrier (bleached hemp fiber) is shown in Figure 1.

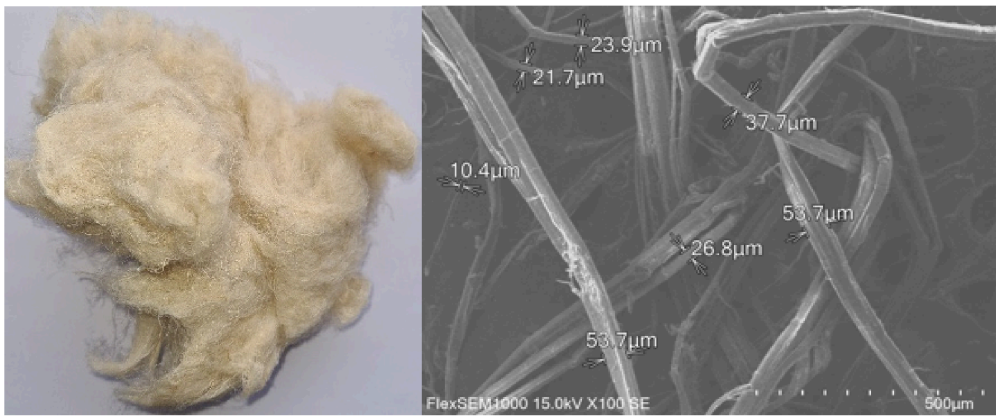

Figure 1. Bleached hemp fiber: general view and scanning electron microscope (SEM) image showing the fiber microstructure [40].

Based on previous experimental studies [40] investigating the sound absorption and transmission properties of bleached hemp fiber with densities ranging from 50 to 250 kg/m^3, determined using impedance tube tests in accordance with standards [47,48], it was found that a 20 mm-thick sample exhibited a sound absorption coefficient ranging from 0.07 to 0.27 in the low-frequency range (160–500 Hz). Higher sound absorption was observed in fibers with higher density. When analyzing the medium frequencies (630–2000 Hz), the sound absorption ranged from 0.35 to 0.90. The highest sound absorption in the medium-frequency range was observed when testing fiber with a density of 150 kg/m^3, reaching up to 0.90 at a frequency of 2000 Hz. When evaluating sound absorption at high frequencies (from 2500 to 5000 Hz), it was observed that the highest efficiency was achieved by medium-density fibers and maximum sound absorption was reached at a frequency of 3150 Hz when using fiber with a density of 100 kg/m^3, where the sound absorption coefficient reached 0.99. Meanwhile, the sound absorption of higher-density fibers was lower when evaluating absorption in the high-frequency spectrum. The sound transmission loss (DTL) of BHF 20 mm over the entire analyzed frequency band (from 160 to 5000 Hz) varied from 16.25 to 25.28 dB for fiber with a density of 250 kg/m^3. Meanwhile, the air resistance of this type of hemp fiber was as follows: 50 kg/m^3—23.5 kPa·s/m^2, 100 kg/m^3—70.8 kPa·s/m^2, 150 kg/m^3—128.0 kPa·s/m^2, 200 kg/m^3—212.5 kPa·s/m^2, and 250 kg/m^3—283.5 kPa·s/m^2 [40]. From the SEM results described in [40], it was found that BHF shows a smooth and clean surface with neatly arranged, straight fiber filaments without surface impurities. The fiber thickness of the bleached fiber was found to range from 6.57 to 53.7 µm [40].

The louvered noise barrier consists of horizontal louvers inclined at a certain angle, which are made of folded metal sheets. The upper part of the louvers is a solid metal plate, while the lower part is a perforated metal plate. A sound-absorbing material is placed inside the louvers; in particular, a perforated plate was placed in the lower part of the louvers to protect the sound-absorbing material from environmental conditions (precipitation, dust, icing). The operating principle of the louvered noise barrier is based on the reflection, absorption, and refraction of incident sound waves (Figure 2). Reflection occurs when a sound wave encounters a boundary between media with different acoustic impedances. Part of the wave is reflected into the original medium, while another part is transmitted into the second medium and partially absorbed. During this interaction, refraction occurs, causing a change in the propagation direction of the sound wave in the new medium; this phenomenon is caused by a change in the speed of sound between media. Sound absorption is directly related to the frequency of the sound waves and depends on the angle at which the waves enter the material.

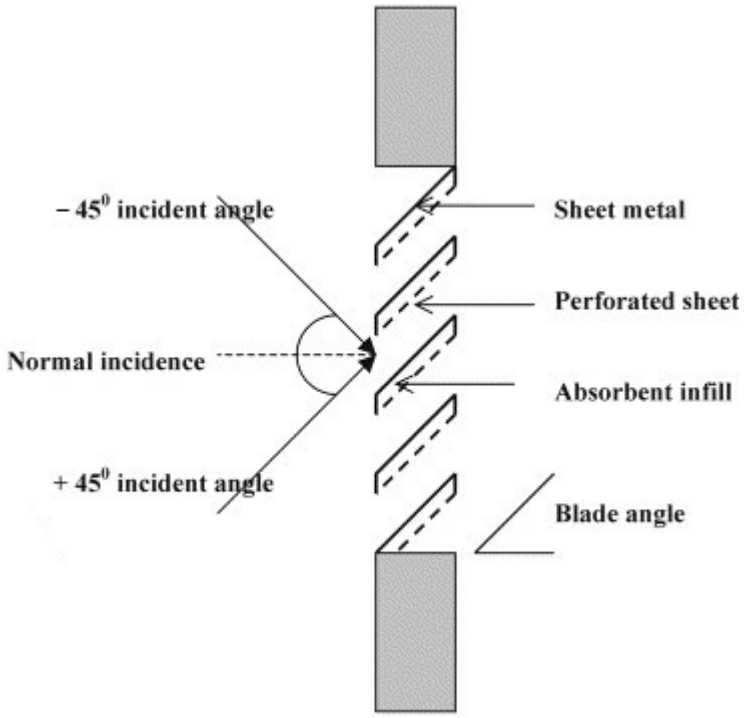

Figure 2. Schematic diagram of the louvered noise barrier and its operating principle [18].

Based on the above-mentioned operating principles of the louvered noise barrier, a louvered noise barrier was designed, the prototype of which was subsequently placed and tested in a semi-anechoic noise-reducing chamber. The dimensions of the designed louvered barrier are 950 mm × 302.5 mm × 822 mm (W × D × H) (Figure 3). The louvered barriers were mounted on four vertical metal profiles, two of which are height-adjustable. By screwing in and out the threaded adjustment mechanism in the profiles, the louver inclination angle of the louvered barriers was adjusted. The possible angles of inclination of the louvered barriers in the structure are shown in Figure 4.

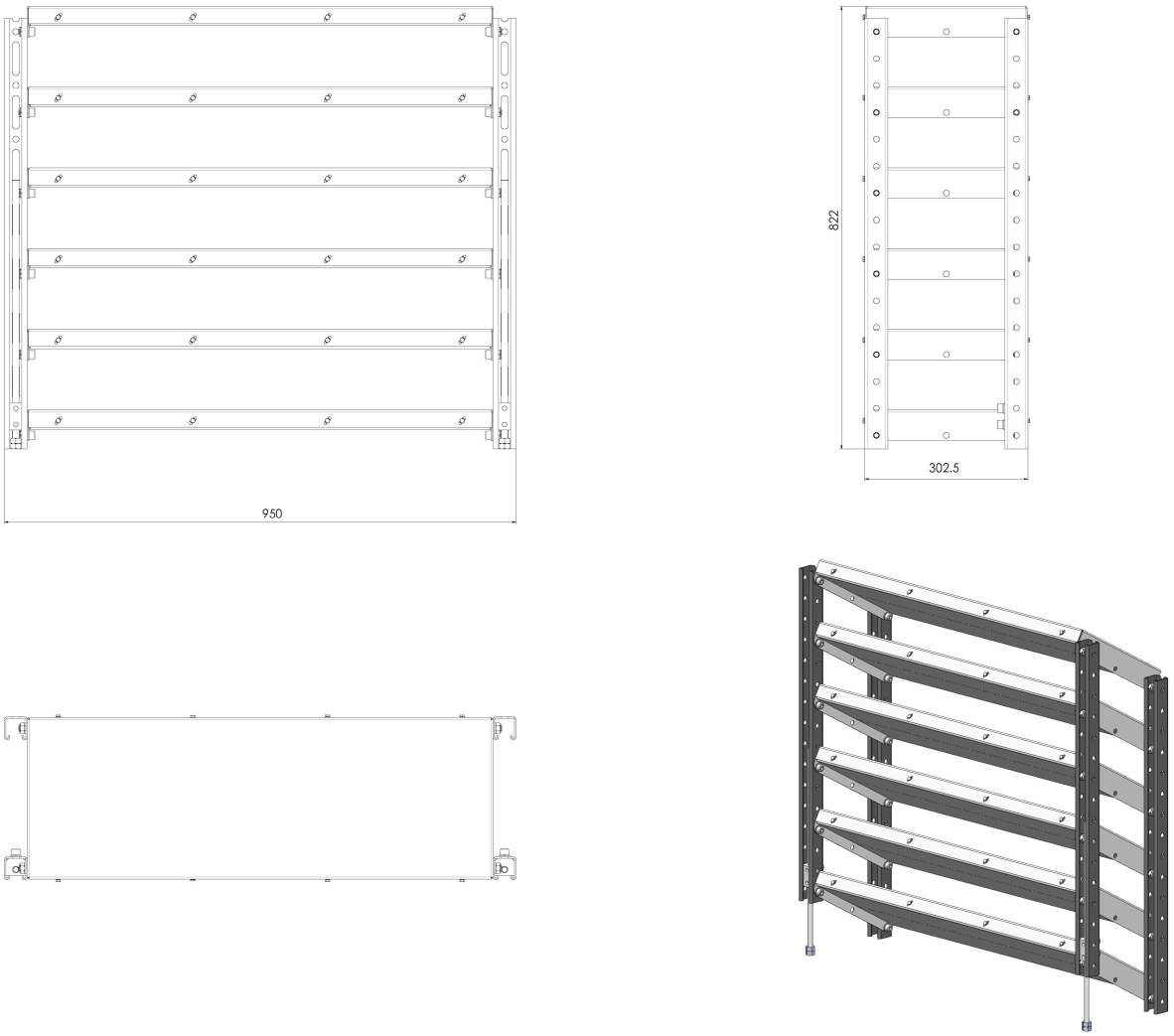

Figure 3. Technical drawing of the designed louvered noise barrier showing front, side, top, and isometric views.

Increasing the angle of inclination reduces the air gap between the louvers, theoretically increasing the efficiency of the barrier in attenuating sound. To obtain the highest efficiency of the noise barrier, the number of louvers can be increased, thus increasing the amount of sound-absorbing material in the structure. The designed barrier currently allows for the use of five, six, or seven louvers, each having a thickness of 30 mm. In such a barrier configuration, the louvers can be adjusted from 0 to 45 degrees, at steps of 15 degrees (Figure 3). The investigated louver inclination angles (0°, 15°, 30°, and 45°) were selected to represent a practical range of louver orientations applicable to ventilated noise barriers, enabling a systematic assessment of the influence of louver geometry on acoustic performance. The investigated hemp fiber densities (50, 100, 150, and 200 kg/m^3) were selected based on previous acoustic characterization studies of bleached hemp fiber, which demonstrated substantial variations in airflow resistivity, sound absorption, and sound transmission properties across this density range [40]. The investigated configurations containing five, six, and seven louvers were selected based on the geometric dimensions of the prototype and to evaluate the influence of increasing the interaction between the propagating sound field and the sound-absorbing material on barrier performance. The minimum gap between the louvers at an angle of 45 degrees is 35 mm.

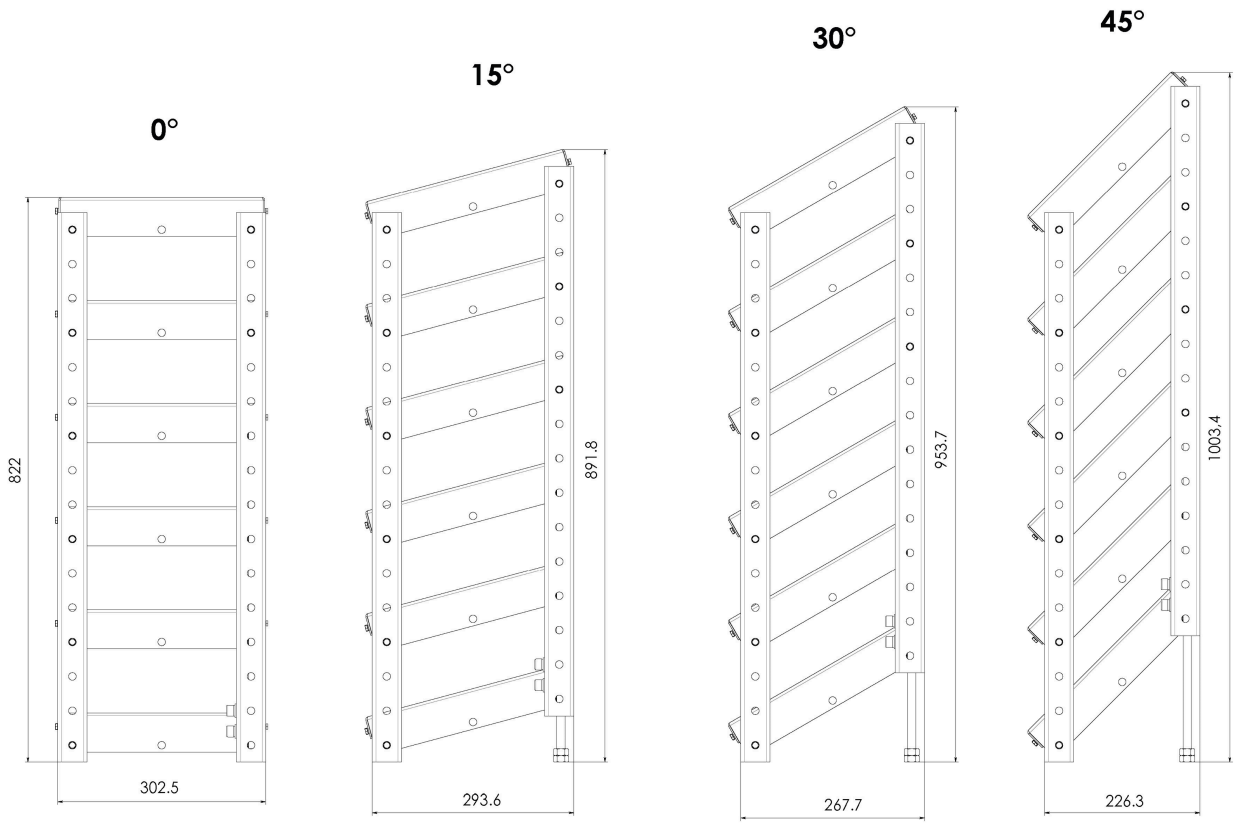

Figure 4. The inclination angle of the louvers in the noise barrier.

The louvers consist of two 2 mm-thick folded metal sheets. The upper sheet is solid metal, while the lower one is perforated metal. To maintain structural strength and performance, an optimal perforation ratio of 35% was selected. Considering that it is not possible to unfold thicker metal sheets and in order not to additionally burden the structure, a 2 mm thick perforated metal sheet with a 5 mm diameter perforation is used. The sheets are connected to each other with rivets (Figure 5). Before the sheets were connected, a sound-absorbing material was placed in the louver.

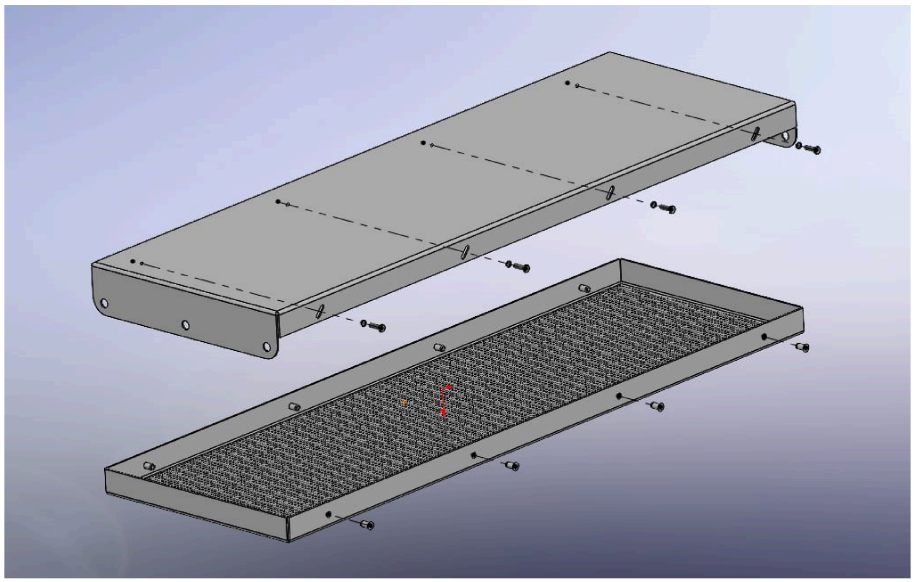

Figure 5. The structure of the louvers in the noise barrier [46].

Knowing the thickness of the louver, the required amount of hemp fiber was weighed, thus selecting the desired density of the sound-absorbing material in the louver. The fiber was placed and pressed between the metal sheets, which were then secured with rivets. To change the density or type of fiber in the louver, the rivets were removed, the tested fiber was removed and the described procedure was repeated. In the designed barrier, the louvers filled with sound-absorbing material are finally fastened with screws to vertical profiles—in the prototype, a wooden frame was used (Figure 6), which was subsequently tested in the semi-anechoic noise reduction chamber.



Figure 6. A prototype of louvered noise barrier under testing.

During the experimental studies, the prototype of the designed structure was tested in the noise reduction chamber to evaluate the influence of hemp fiber density on its performance, as well as to determine the optimal number of louvers and their inclination angle. Different configurations of the prototype of the noise barrier were tested, with either five, six, or seven louvers. Each configuration was tested by changing the density of the hemp fiber in the louvers from 50 to 200 kg/m^3 in steps of 50 kg/m^3, and by turning the louvers to an angle of 0, 15, 30, or 45 degrees.

2.2. Methodology for Determining the Acoustic Parameters of a Louvered Noise Barrier Prototype in a Semi-Anechoic Chamber

Based on the louver volume, the required amount of fiber was weighed and placed in the louver to achieve the desired fiber density (Figure 7). The hemp fiber was carefully placed into the louvers by hand, evenly distributing the material throughout the louver volume to avoid density irregularities. To match the louver dimensions, the fiber was pressed by hand to the height of the louver, without using additional pressing devices. The mass and density error of the hemp fiber samples did not exceed ±1%. The degree of compression was controlled by the geometric dimensions of the louver.



Figure 7. Louvers filled with bleached hemp fiber.

The louvers were then placed in a wooden prototype frame. The prototype was then placed and tested in a semi-anechoic chamber. A view of the chamber in the receiving and transmitting room is shown in Figure 7. The tests are performed according to the ISO 10140 standard [49], and the measurements were made under standard laboratory conditions at a temperature of 23 ± 2 °C and a relative humidity of 50 ± 5%.

The semi-anechoic noise reduction chamber was divided by a wall into two rooms: a sound source room and a sound receiving room (Figure 8). The interior of the sound receiving room was covered with acoustic foam panels. The height of the wedge of panels was 250 mm, and the distance from one wedge tip to the next was 150 mm. The chamber was 4 m long, 2.5 m wide, and 3 m high. The rooms of the noise chamber were insulated from each other and externally, thus limiting extraneous noise. A 1 m^2 opening was installed in the wall separating the receiving and transmitting sound rooms, and the 1.0 m × 1.0 m test structure was attached to it.



Figure 8. General view of the noise chamber in the sound receiving and sound source room.

A microphone was placed in the sound receiving room and an omnidirectional loudspeaker was placed in the sound source room, which created a constant diffuse sound field. The spectrum of this sound field did not change over the entire frequency range and was continuous. Experimental studies were carried out using high-precision equipment from the Danish manufacturer Brüel & Kjær: the sound source "Brüel & Kjær OmniPower

Sound Source Type 4292-L (Brüel & Kjær Sound & Vibration Measurement A/S, Nærum, Denmark)", the amplifier "Brüel & Kjær Type 2734 (Brüel & Kjær Sound & Vibration Measurement A/S, Nærum, Denmark)", and the noise level analyzer "Bruel & Kjaer 2270 (Brüel & Kjær Sound & Vibration Measurement A/S, Nærum, Denmark)". The measuring device complied with standards IEC 61672 [50], IEC 60651 [51], and IEC 60804 [52].

Studies of the louver structure in the semi-anechoic chamber were carried out according to [49], using the microphone sweeping or rotating method. The rotating method allows for the averaging of sound pressure levels at different locations in space, thus avoiding the influence of standing waves and covering different areas of the diffuse field in the receiving room. The rotation lasted at least 15 s during each measurement session. One microphone was used, which remained at the same distance from the sample (1.0 m) during rotation. Four separate rotations were performed in each room. The reverberation time (at least six different microphone positions in the receiving room) and the background noise in the receiving room (one position) were also evaluated. All measurements for each investigated barrier configuration were performed repeatedly, in accordance with the methodology described above.

To determine the efficiency of the structure under study, the following parameters were determined:

- Apparent sound (R′) and weighted sound reduction index (Rw);
- Insertion loss (IL);
- Equivalent sound level loss (LAeq).

The equivalent sound pressure level in a room is defined as the base-10 logarithm of the ratio of the spatial and temporal mean-square value of the sound pressure to the square of the reference sound pressure, where the spatial average is determined over the entire room volume. This quantity is denoted by L and is expressed in decibels. The equivalent sound pressure level (LAeq) is calculated using the following formula:

$$\mathrm{LAeq} = 10\mathrm{lg}\left[\frac{1}{T_m}\int_0^{T_m}\left(\frac{p^2(t)}{p_0^2}\right)dt\right], \quad (1)$$

$$\mathrm{LAeq} = 10\mathrm{lg}\left(\frac{1}{n}\sum_{i=1}^{n} 10^{\frac{L_i}{10}}\right), \quad (2)$$

where T—measurement time (in seconds);

$L_{(t)}$—instantaneous noise level (dBA) at a given time t;

$p_1, p_2, \ldots, p_n$—root mean square sound pressure values at n different locations in the room;

p_0—reference sound pressure value, $p_0 = 2 \times 10^{-5}$ Pa.

The reduction in equivalent sound level (LAeq) is defined as the difference between the equivalent continuous noise level measured in the receiving room without louvers (LAeq1) and the sound level measured after the louvers have been installed (LAeq2).

The equivalent sound level loss results are presented in the graphs together with standard deviation error bars. The standard deviation of the equivalent sound level loss (LAeq) was calculated using:

$$SD_{LAeq} = \sqrt{SD_{LAeq1}{}^2 + SD_{LAeq2}{}^2} \quad (3)$$

The overall sound attenuation efficiency of the designed barrier was tested in the noise chamber, which was measured to determine the frequency range that the design attenuates most effectively. The sound insulation level of the louvered noise barrier was

determined in accordance with the standard ISO 10140-4:2021 [49], which provides the basic measurement methods and procedures required to determine sound insulation under laboratory conditions. Sound pressure levels were measured in the source and receiving rooms. The average sound pressure level was calculated in both rooms (with background noise correction applied), and the sound reduction index (R′) of the barrier was determined using

$$R' = L_1 - L_2 + 10 \cdot \log_{10}(S/A), \quad (4)$$

where S—sample area (m^2);

L_1—sound pressure level in the sound source room;

L_2—sound pressure level in the sound receiving room;

A—sound absorption area in the sound receiving room.

A is calculated from the reverberation time as follows:

$$A = 0.16 \cdot V/T_{60} \quad (5)$$

where A—sound absorption area in the sound receiving room (m^2);

V—room volume (m^3);

T_{60}—reverberation time (s).

The weighted sound reduction index (R′w) was determined by fitting a standard reference curve to the measured sound insulation index values at various frequencies, as specified in ISO 717-1 [53]. The R′w values are reported together with the corresponding measurement uncertainties.

The insertion loss was calculated as the difference between the sound pressure level measured in the sound receiving room without the louvered noise barrier and that with the noise barrier. Insertion loss was calculated using Formula (6), as described in ISO 11691 [54]:

$$IL = L_{p1} - L_{p2}, \quad (6)$$

where L_{p1} is the sound pressure level without the louvered noise barrier and L_{p2} is the sound pressure level with the louvered noise barrier.

The sound reduction and sound insertion loss results are presented in a 1/3 octave frequency band, at frequencies ranging from 100 to 5000 Hz.

The insertion loss (IL) results are presented in the graphs together with standard deviation error bars. The standard deviation of the IL was calculated using error propagation principles. Since the insertion loss was determined as the difference between two independently measured sound pressure levels ($IL = L_{p1} - L_{p2}$), the corresponding standard deviation was calculated as

$$SD_{IL} = \sqrt{SD_{Lp1}{}^2 + SD_{Lp2}{}^2} \quad (7)$$

where $SD_{L_{p1}}$ and $SD_{L_{p2}}$ are the standard deviations of the respective measured sound pressure levels.

3. Results

3.1. Sound Insertion Loss Results for the Louvered Noise Barriers

According to the barrier design solutions and development aspects described above, a prototype louvered noise barrier was manufactured, corresponding to the designed barrier. The prototype was made of a wooden frame, into which louvers filled with bleached hemp fiber (BHF) were inserted. The prototype was designed according to the dimensions of the designed barrier, the number of louvers, and the intended angles of inclination of the

louvers. The louvered barrier was easy to assemble, could be adjusted in terms of the required angle of inclination of the louvers, and the sound-absorbing material and number of louvers in the structure could be changed.

For the experimental studies in the noise reduction chamber, a louvered noise barrier with bleached hemp fiber (BHF) was investigated. The structure consisted of five, six, or seven louvers; the louvers in the structure were turned at an angle of 0, 15, 30, or 45 degrees; and the fiber density in different structural configurations of the barrier was 50, 100, 150, or 200 kg/m^3. With all possible combinations, 48 insertion loss (IL), 48 sound reduction index (R′), and 48 equivalent sound level loss (LAeq) measurements were performed for the louvered noise barrier. After measuring the sound reduction index, the weighted sound reduction index (R′w) was calculated according to ISO 717-1 [53]. The sound insertion loss (IL) results for the barriers with 50 kg/m^3 BHF are presented in Figure 9.

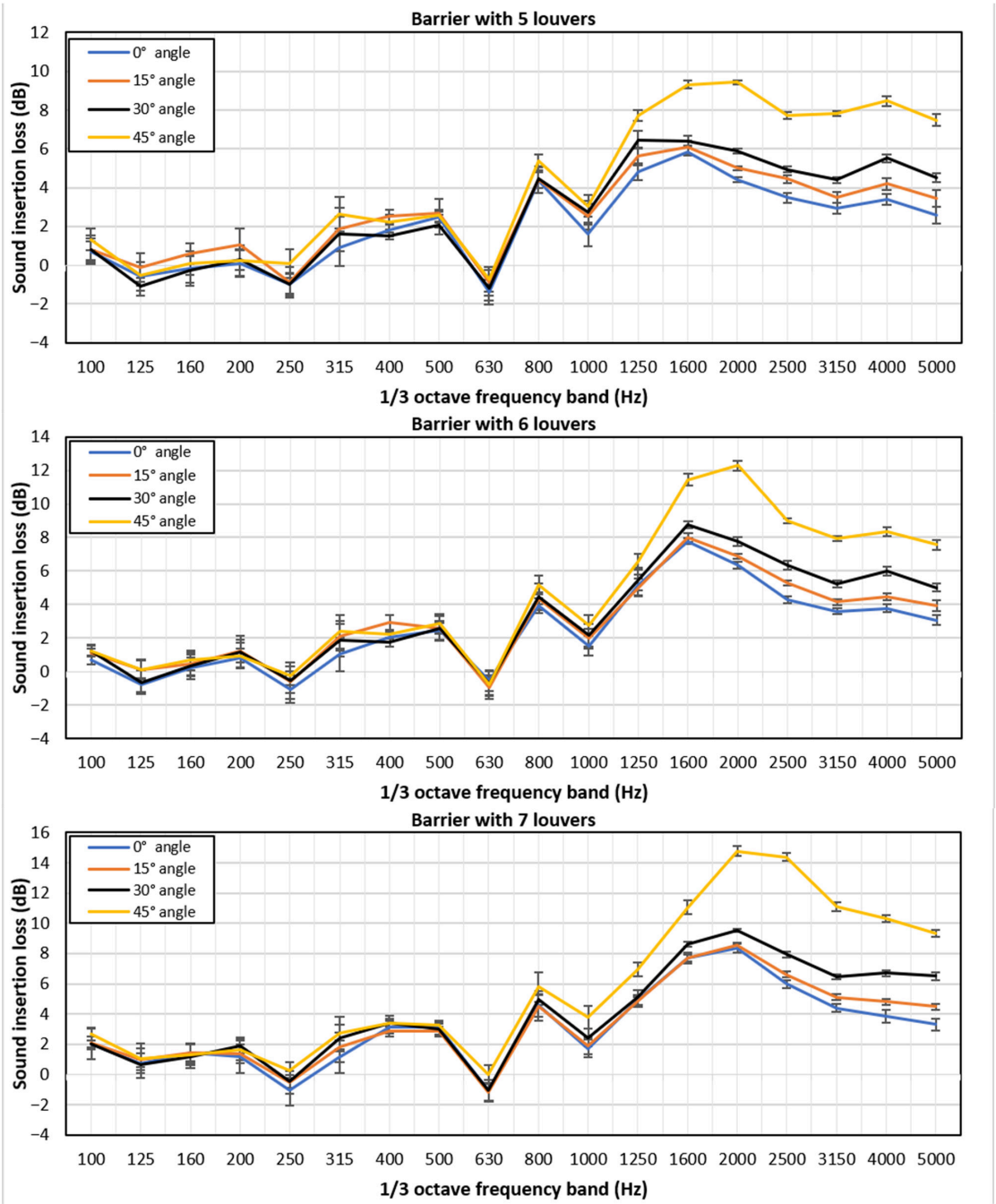

Figure 9. Sound insertion loss (IL) results for the barriers with 50 kg/m^3 BHF.

From the sound insertion loss (IL) results for the barriers with 50 kg/m^3 BHF (Figure 9), the values in the low-frequency range (from 100 to 500 Hz) were similar. When evaluating barriers with different numbers of louvers, the IL at low frequencies reached up to 2.68 dB with five louvers, 2.92 dB with six louvers, and 3.42 dB with seven louvers. These results were similar because low-frequency sound waves propagated through the barriers, thus creating resonance phenomena, and also because the barrier design is not very effective for absorbing the long wavelengths characterizing low frequencies. For this reason, a direct influence of the louver tilt angle on the IL results in the low-frequency range was also not observed. In the mid-frequency range (from 500 to 1600 Hz), a rapid increase in IL was observed at 1000 Hz in all cases. At this frequency, the acoustic wavelength in air is approximately 0.34 m, comparable with the characteristic dimensions of the louvered barrier. As the wavelength comes closer to the dimensions of the structure, the interaction between the sound wave and the barrier becomes more significant. At this frequency, a direct influence of the louver tilt angle on the insertion loss began to be observed. Increasing the angle of inclination of the louvers also improved the result. When evaluating the barrier structures with five and six louvers turned at angles of 0, 15, and 30 degrees, the peak IL was reached at 1250 and 1600 Hz, reaching o 8.78 dB at an angle of 30 degrees with six louvers. Meanwhile, the absolute IL peak was reached in all cases in the high-frequency range (1600–5000 Hz) when the barrier louvers were turned at an angle of 45 degrees. The peak IL was observed at a frequency of 2000 Hz, where it reached 6.44 dB with five louvers, 11.43 dB with six louvers, and 14.77 dB with seven louvers. The most pronounced influence of the louver's inclination angle on the efficiency of the structure was also observed in the high-frequency range. For example, at a frequency of 2000 Hz, the IL of the barriers with seven louvers reached 8.33 dB at a 0-degree angle, 8.53 dB at a 15-degree angle, 9.53 dB at a 30-degree angle, and 14.77 dB at a 45-degree angle. In particular, the IL increased by 1.77 times when the louvers were turned from a 0-degree angle to a 45-degree angle.

Figure 10 presents the sound IL results for the barriers with 100 kg/m^3 BHF. In principle, for the reasons described above, the IL in the low-frequency range remained similar to that with the barriers including 50 kg/m^3 fiber, reaching up to 4.57 dB (seven louvers)—slightly more than the previously determined IL of 3.42 dB, which can be attributed to the increased density of the hemp fiber. At the critical frequency of 1000 Hz, an increase in the IL was again observed, while peaks were reached in the frequency range of 1250–2000 Hz. As before, the most pronounced influence of the angle of inclination of the louvers on the efficiency of the structure was observed in the high-frequency range. The peak ILs for the barrier with seven louvers reached 10.67 dB at a 0-degree angle, 10.55 dB at a 15-degree angle, 11.38 dB at a 30-degree angle, and 18.13 dB at a 45-degree angle. As a result, the IL increased by 1.70 times when the louvers were turned from a 0-degree angle to a 45-degree angle. Meanwhile, the peak ILs for the barrier with six louvers reached 8.98, 9.35, 11.22, and 16.89 dB, respectively, indicating a 1.88-fold increase when changing the angle from 0 to 45 degrees. When evaluating the barrier with five louvers, the peak ILs were 7.02, 7.29, 8.27, and 9.67 dB, respectively, which meant a 1.38-fold increase when increasing from 0 to 45 degrees. In this case, changing the louver angle had the greatest impact in the structure with six louvers. A comparison of the results revealed that, when increasing the number of louvers from five to seven, the maximum IL increased from 9.67 to 18.13 dB, demonstrating an increase of 1.87 times. Comparing the maximum IL determined when using fiber with 50 and 100 kg/m^3 density, the maximum IL increased from 14.77 to 18.13 dB when the structure consisted of seven louvers at an angle of 45 degrees. The results indicate that the IL of the structure was most influenced by the number of louvers, which resulted in an increased surface area interacting with the propagating sound

wave and a greater amount of material, resulting in higher sound wave energy losses and increased attenuation.

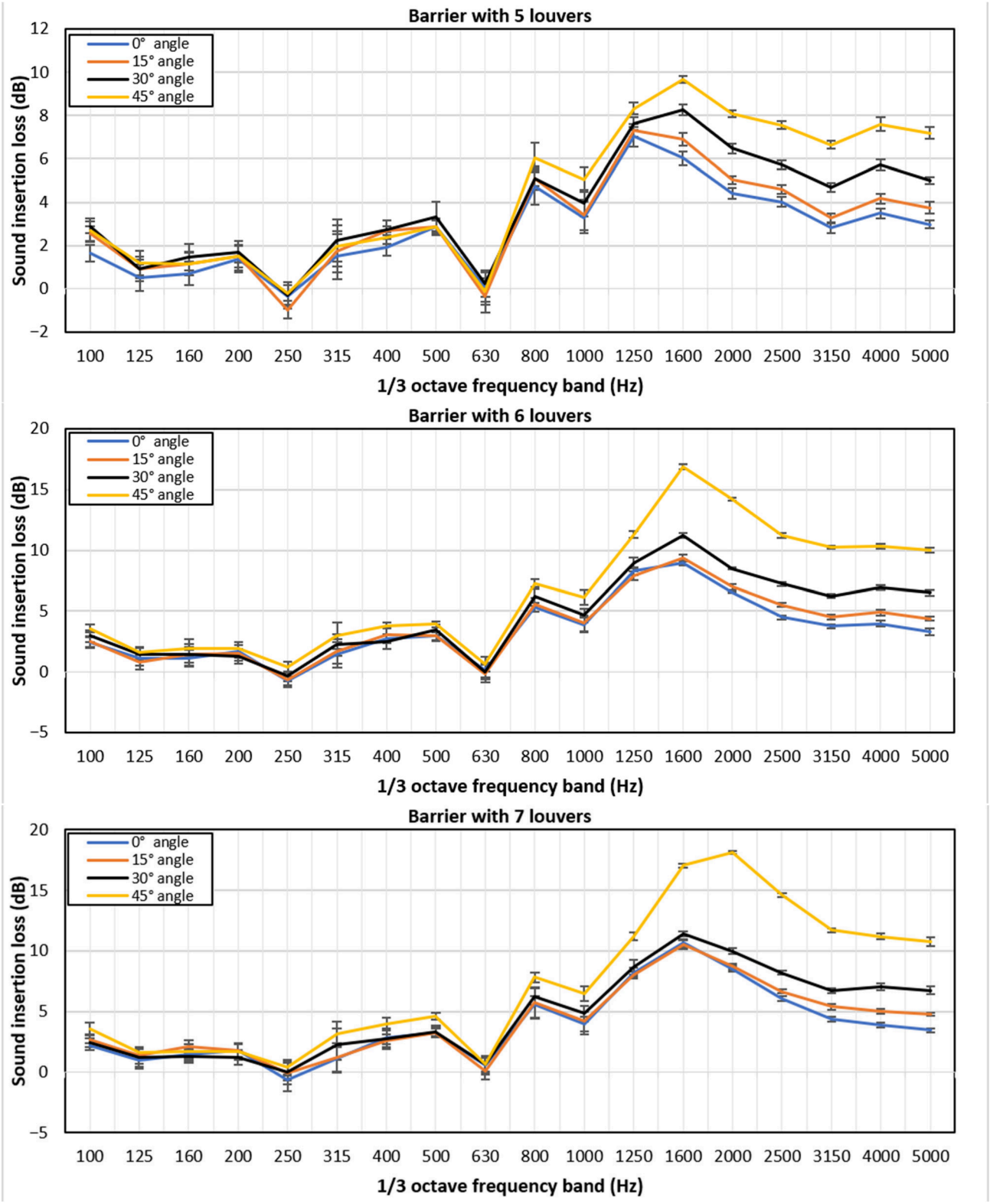

Figure 10. Sound insertion loss (IL) results for the barriers with 100 kg/m^3 BHF.

Analyzing the sound IL results for the barriers with 150 kg/m^3 BHF (Figure 11), it was observed that the situation remained stable at low frequencies, although a slight increase in IL was noted. In particular, the IL at 500 Hz reached 5.05 dB, which was attributed to the

increased density of hemp fibers improving the sound absorption and insulation properties in the low-frequency range. In general, the results for all three designs (i.e., with five, six, or seven louvers) in the low- and medium-frequency range (up to 1000 Hz) were quite similar, and peak ILs were observed in all cases at 1600 Hz.

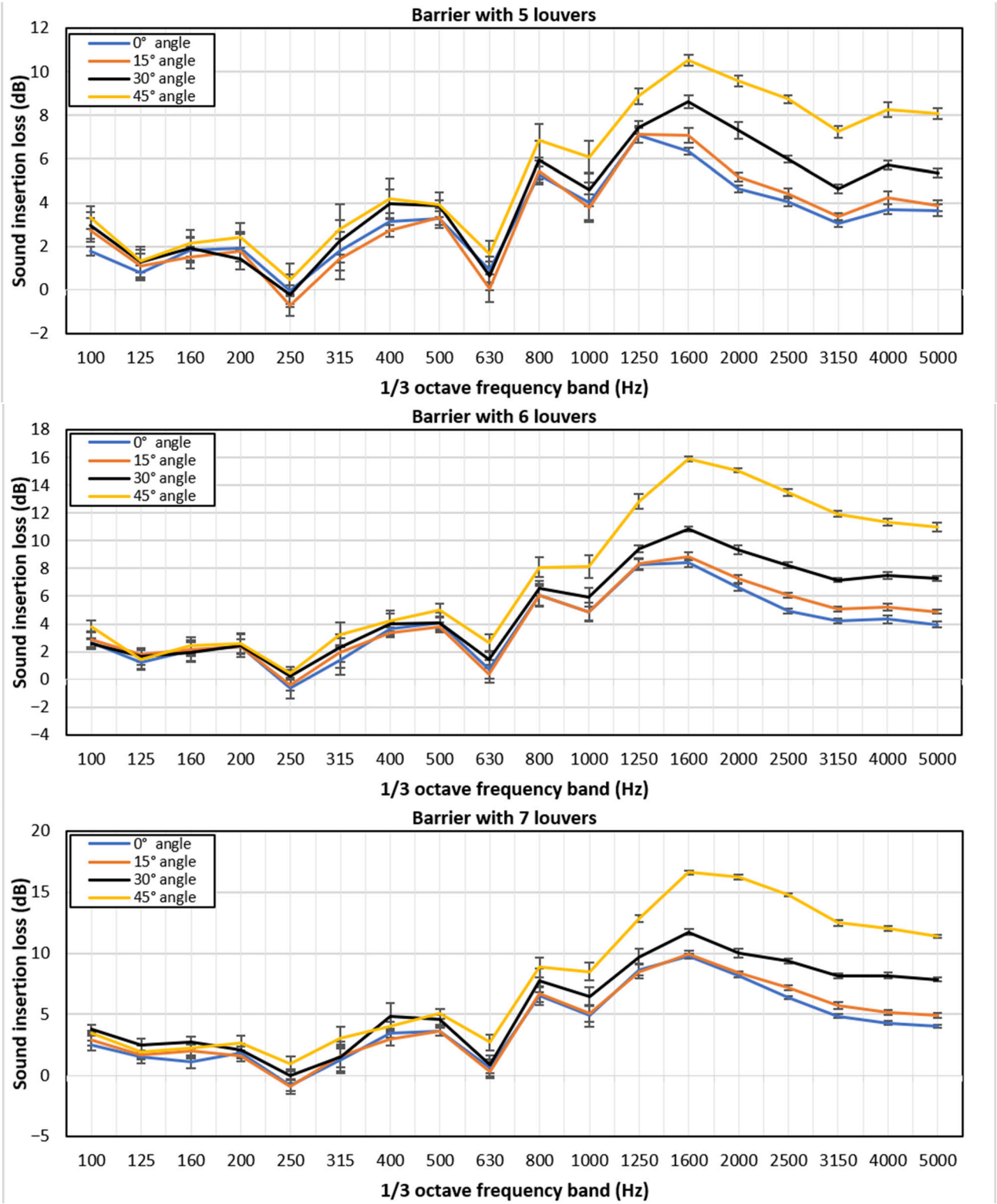

Figure 11. Sound insertion loss (IL) results for the barriers with 150 kg/m^3 BHF.

The peak ILs for the barriers with five louvers reached 7.08 dB at a 0-degree angle, 7.13 dB at a 15-degree angle, 8.62 dB at a 30-degree angle, and 10.53 dB at a 45-degree angle. Meanwhile, the peak ILs for the barriers with six louvers reached 8.39, 8.86, 10.84, and 15.88 dB, respectively; when evaluating the barriers with seven louvers, the peaks reached 9.76, 9.89, 11.72, and 16.6 dB, respectively. The maximum determined IL for the barriers with seven louvers and 150 kg/m^3 hemp fiber reached 16.6 dB (at a 45-degree tilt angle), while that for the barriers with seven louvers and 100 kg/m^3 density hemp fiber reached 18.13 dB; i.e., the maximum IL of the louver barrier decreased by 8.4%. This may be explained by the fact that according to [40], increasing the density of hemp fiber increases its air resistance (100 kg/m^3—70.8 kPa·s/m^2, 150 kg/m^3—128.0 kPa·s/m^2) and, at the same time, although the insulation properties of the fiber increased over the entire frequency range, the sound absorption properties in the high-frequency range decreased slightly while increasing in the medium- and low-frequency ranges. As a result, the ILs for the barriers with 150 kg/m^3 BHF slightly decreased at the frequencies where the peak was determined but increased slightly at low frequencies.

When evaluating the sound IL results for the barriers with 200 kg/m^3 BHF (Figure 12), a slight increase in the IL was observed at a frequency of 400 Hz, reaching 5.87 dB. The peak ILs for the barriers with five louvers reached 6.02 dB at a 0-degree angle, 6.64 dB at a 15-degree angle, 7.78 dB at a 30-degree angle, and 9.48 dB at a 45-degree angle. Meanwhile, the peak ILs for the barriers with six louvers reached 7.65, 7.94, 9.39, and 14.05 dB, respectively; when evaluating the barriers with seven louvers, the peaks reached 8.75, 9.31, 12.3, and 14.76 dB, respectively. The maximum determined IL of the barriers with seven louvers and 200 kg/m^3 hemp fiber was 14.76 dB (at a 45-degree tilt angle), while that for the barriers with seven louvers and 100 kg/m^3 density hemp fiber reached 18.13 dB; i.e., the maximum IL of the louver barrier decreased by 18.6%. The IL results obtained for the barriers with 200 kg/m^3 BHF were similar to those for the barriers with 50 kg/m^3 density BHF, with the peak IL reaching 14.77 dB. The IL values for the barriers with 200 kg/m^3 BHF decreased at the frequencies where the peak was determined but increased slightly at low frequencies. Based on the IL results, it was concluded that the optimal hemp fiber density was 100 kg/m^3, which allowed for a peak IL of 18.13 dB at 2000 Hz when using seven louvers turned at a 45-degree angle with respect to the noise source in the barrier structure.

3.2. Sound Reduction Results for the Louvered Noise Barriers

To more accurately assess the noise reduction properties of the louvered barriers with hemp fiber, apparent sound reduction index (R′) measurements were performed. Applying a standard reference curve to the measured sound reduction index values at various frequencies, as specified in the ISO 717-1 standard [38], the weighted sound reduction index R′w was determined.

The apparent sound reduction index (R′) and weighted sound reduction index (R′w) results for the barriers with 50 kg/m^3 density BHF are presented in Figure 13. In the low-frequency range (100–500 Hz), the situation remained similar to the IL results. As before, these results may be explained by the fact that low-frequency sound waves propagating through the barrier created resonance phenomena, as well as the poor ability of the barrier structure to absorb low frequencies characterized by long wavelengths. In the low-frequency range, for this reason, no direct influence of the louver tilt angle on the result was noted. In the mid-frequency range, in all cases, the R′ value of the structure began to increase at a frequency of 1000 Hz, and a clear influence of the louver tilt angle on the result was also observed. In the high-frequency range (1600–5000 Hz), maximum R′ values were observed. In all cases, regardless of the number of louvers, the highest values were observed when the louvers were turned at an angle of 45 degrees with respect to the noise

source. When the structure consisted of five louvers, the highest R′ value reached 15.4 dB at a frequency of 4000 Hz. When the structure consisted of six louvers, the highest R′ value reached 17.1 dB at a frequency of 2000 Hz. When the structure consisted of seven louvers, the highest R′ value reached 19.7 dB at a frequency of 2500 Hz. Meanwhile, when the louvers were turned at an angle of 45 degrees, the weighted sound reduction index (R′w) reached 10.5 dB with five louvers, 10.7 dB with six louvers, and 11.5 dB with seven louvers.

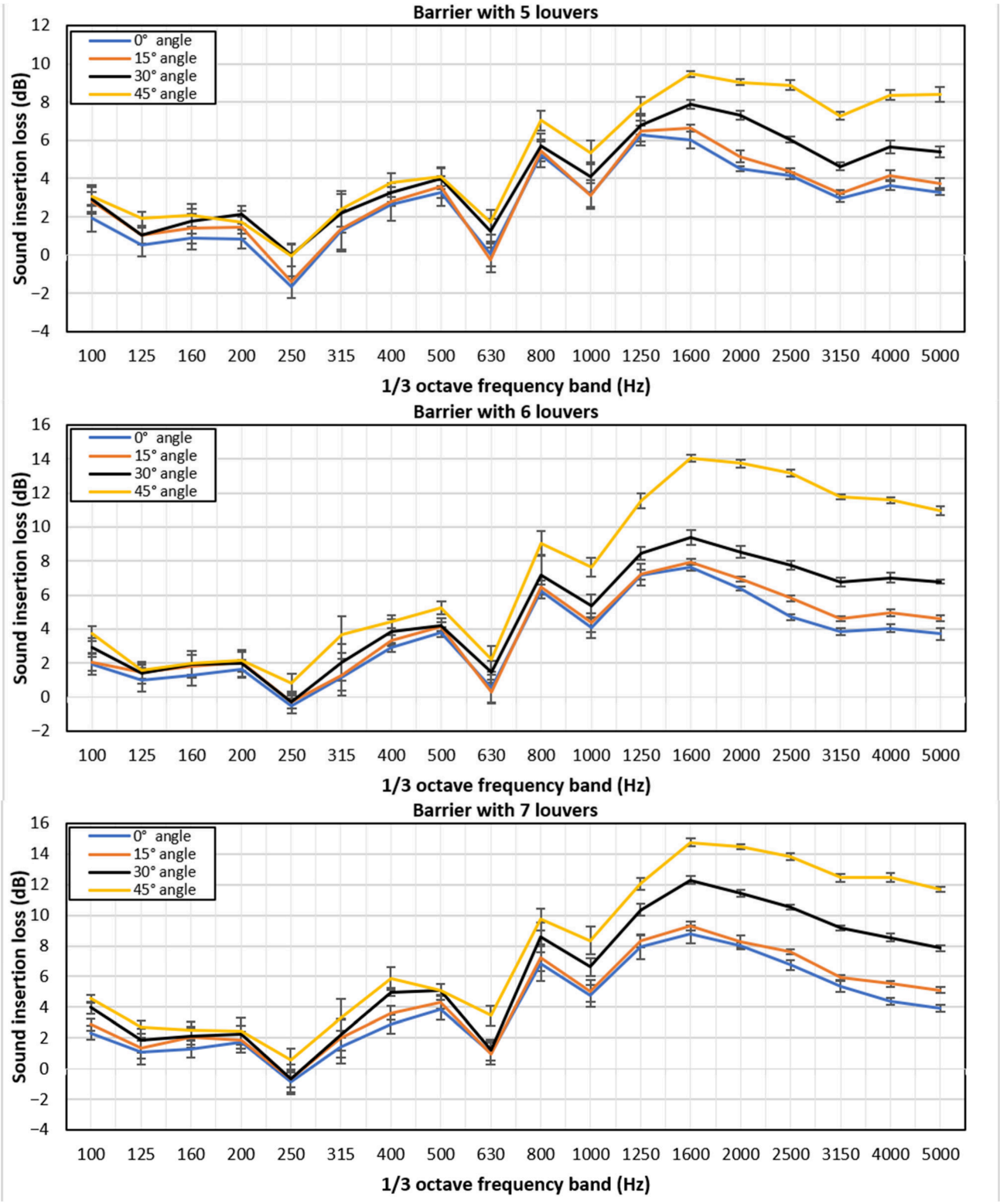

Figure 12. Sound insertion loss (IL) results for the barriers with 200 kg/m^3 BHF.

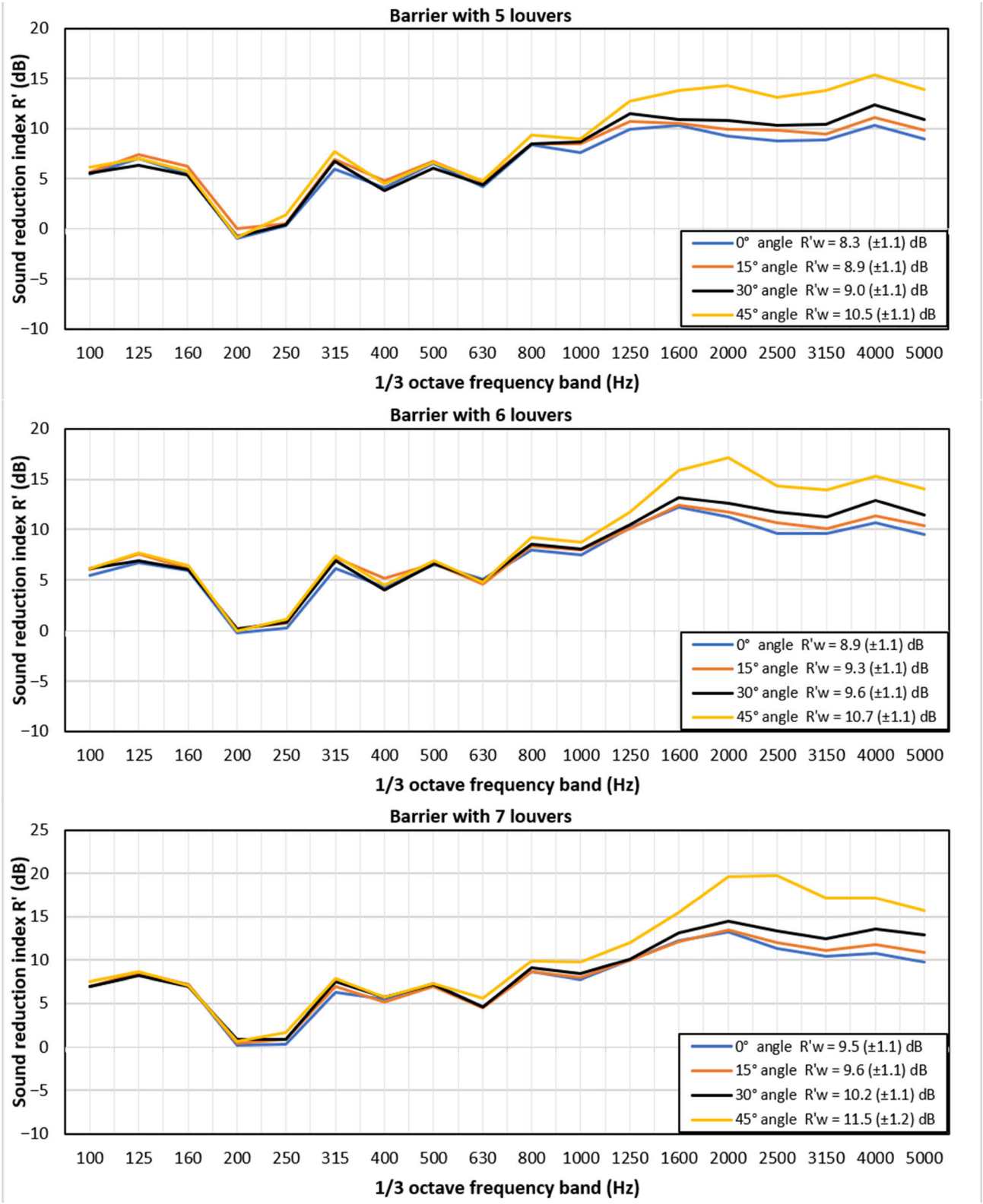

Figure 13. Apparent sound reduction index (R′) and weighted sound reduction index (R′w) results for the barriers with 50 kg/m^3 BHF.

The apparent sound reduction index (R′) and weighted sound reduction index (R′w) results for the barriers with 100 kg/m^3 density BHF are presented in Figure 14.

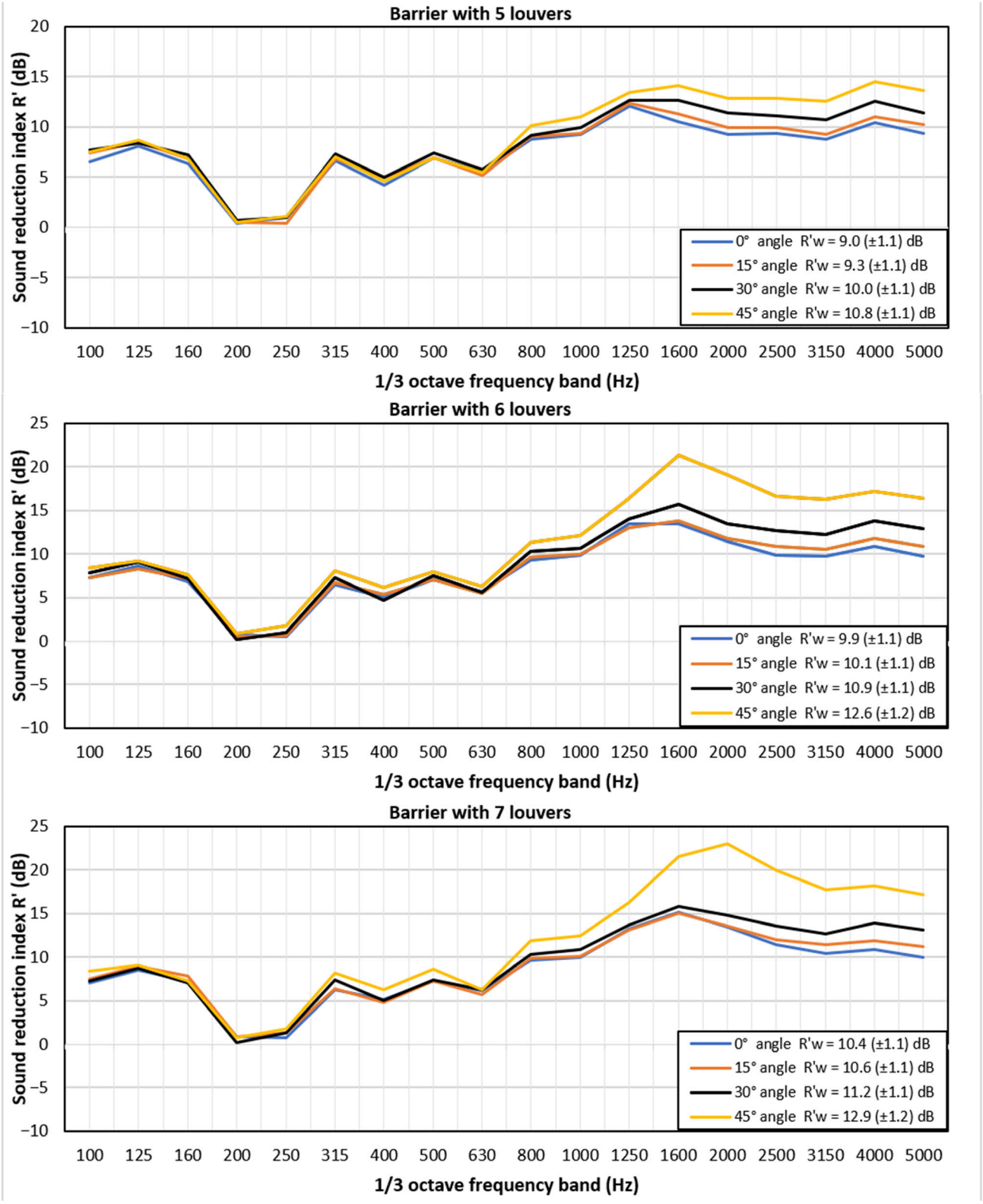

Figure 14. Apparent sound reduction index (R′) and weighted sound reduction index (R′w) results for the barriers with 100 kg/m^3 BHF.

In the low-frequency range (from 100 to 500 Hz), the apparent sound reduction index (R′) of the louvered noise barriers reached up to 8.7 dB with five louvers, 8.4 dB with six louvers, and 9.1 dB with seven louvers. At frequencies of 200 and 250 Hz, a decrease in R′ was observed due to resonance occurring at low frequencies. At low and medium

frequencies, the apparent sound reduction index for all barriers was similar, and similar trends were observed. In all cases, the highest R′ values were determined when turning the louvers at an angle of 45 degrees. Peak values were observed at frequencies of 4000, 2000, and 2500 Hz, regardless of the louver inclination angle. When the structure consisted of five louvers, the highest R′ value reached 14.5 dB at a frequency of 4000 Hz. When the structure consisted of six louvers, the highest R′ value reached 21.3 dB at a frequency of 1600 Hz. When the structure consisted of seven louvers, the highest R′ value reached 23.0 dB at a frequency of 2000 Hz. Meanwhile, when the louvers were turned at an angle of 45 degrees, the weighted sound reduction index (R′w) reached 10.8 dB with five louvers, 12.6 dB with six louvers, and 12.9 dB with seven louvers. When comparing the highest R′ results with those determined when testing the structure with 50 kg/m^3 hemp fiber, a significant increase was observed: the highest value determined when testing the structure with seven louvers and a 45 degree tilt angle increased from 19.7 to 23.0 dB, while the R′w value increased from 11.5 to 12.9 dB.

When examining the structures with louvers filled with 150 kg/m^3 density BHF (Figure 15), the highest R′ value was determined to be 15.2 dB at a frequency of 4000 Hz for the structure consisting of five louvers. When the structure consisted of six louvers, the highest R′ value reached 20.3 dB at a frequency of 1600 Hz. When the structure consisted of seven louvers, the highest R′ value reached 21.1 dB at a frequency of 2000 Hz. Meanwhile, when the louvers were turned at an angle of 45 degrees, the weighted sound reduction index (R′w) reached 11.8 dB with five louvers, 13.7 dB with six louvers, and 13.1 dB with seven louvers. When comparing the highest R′ results with those determined when testing the structure with 100 kg/m^3 hemp fiber, a slight decrease was observed: the highest value determined when testing the structure with seven louvers and a 45-degree tilt angle decreased from 23.0 dB to 21.1 dB. The slight decrease in the peak R′ value, as in the analysis of the IL results, can be explained by the fact that although increasing the density of the hemp fiber increases its insulation properties over the entire frequency range, the sound absorption properties in the high-frequency range decrease slightly while increasing in the medium- and low-frequency ranges. As a result, the sound reduction index results for the barriers with 150 kg/m^3 BHF decreased at the frequencies where the peak was determined but increased slightly for low and medium frequencies. As a result, the R′w value increased from 11.5 to 13.1 dB.

Figure 16 presents the apparent sound reduction index (R′) and weighted sound reduction index (R′w) results for the barriers with 200 kg/m^3 density BHF, from which it can be seen that the trends are similar to those observed for 150 kg/m^3 BHF. It was observed that increasing the density decreased the R′ value at high frequencies and, when the structure consisted of five louvers, the R′ value was 14.8 dB at 4000 Hz.

When the structure consisted of six louvers, the maximum R′ value reached 18.6 dB at 2000 Hz. When the structure consisted of seven louvers, the maximum R′ value reached 19.4 dB at 2000 Hz. This means that compared with barriers with 100 kg/m^3 density BHF, the maximum R′ value decreased from 23.0 to 19.4 dB. Meanwhile, when the louvers were turned at a 45-degree angle, the weighted sound reduction index (R′w) reached 11.5 dB with five louvers, 13.6 dB with six louvers, and 14.1 dB with seven louvers.

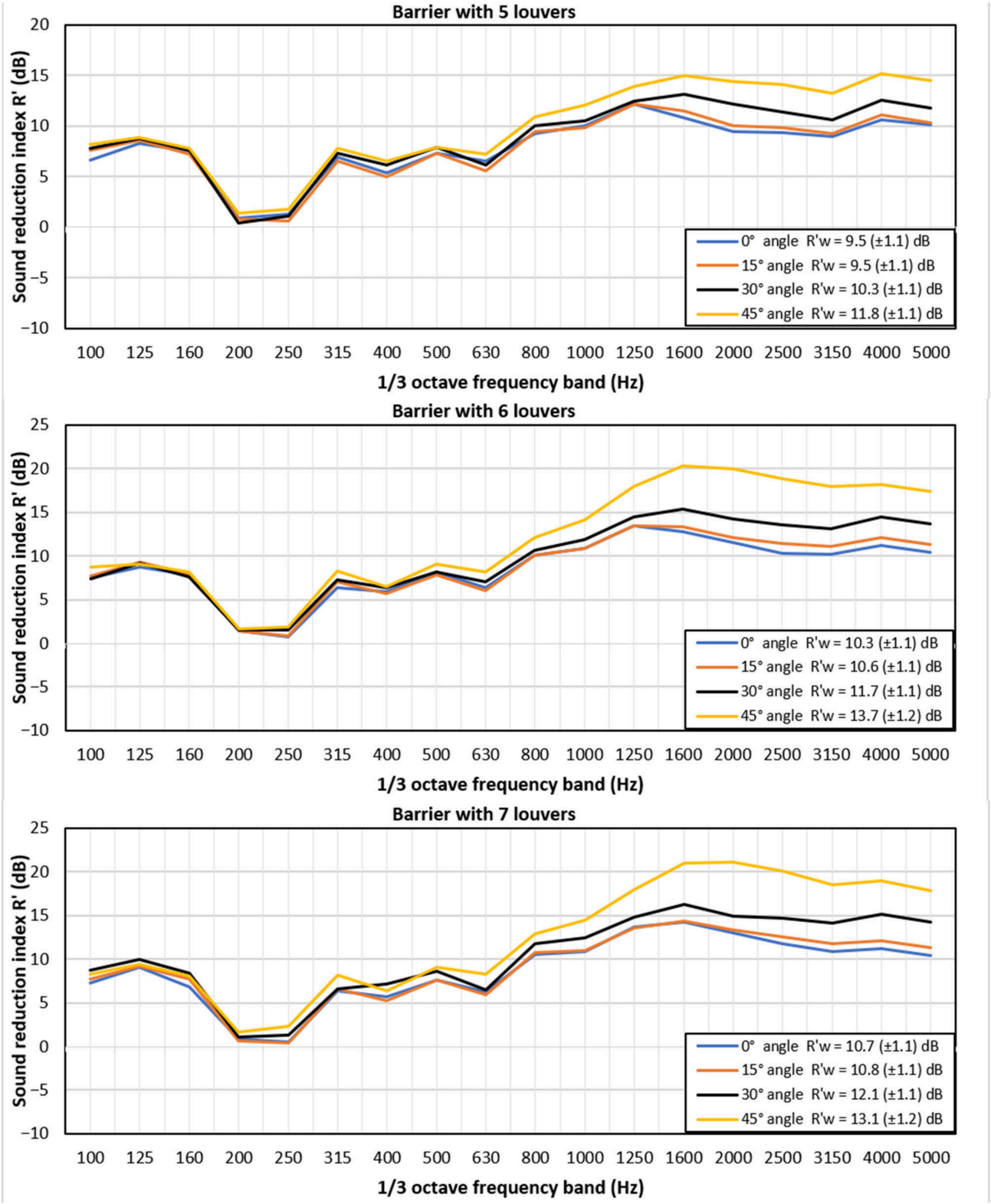

Figure 15. Apparent sound reduction index (R′) and weighted sound reduction index (R′w) results for the barriers with 150 kg/m^3 BHF.

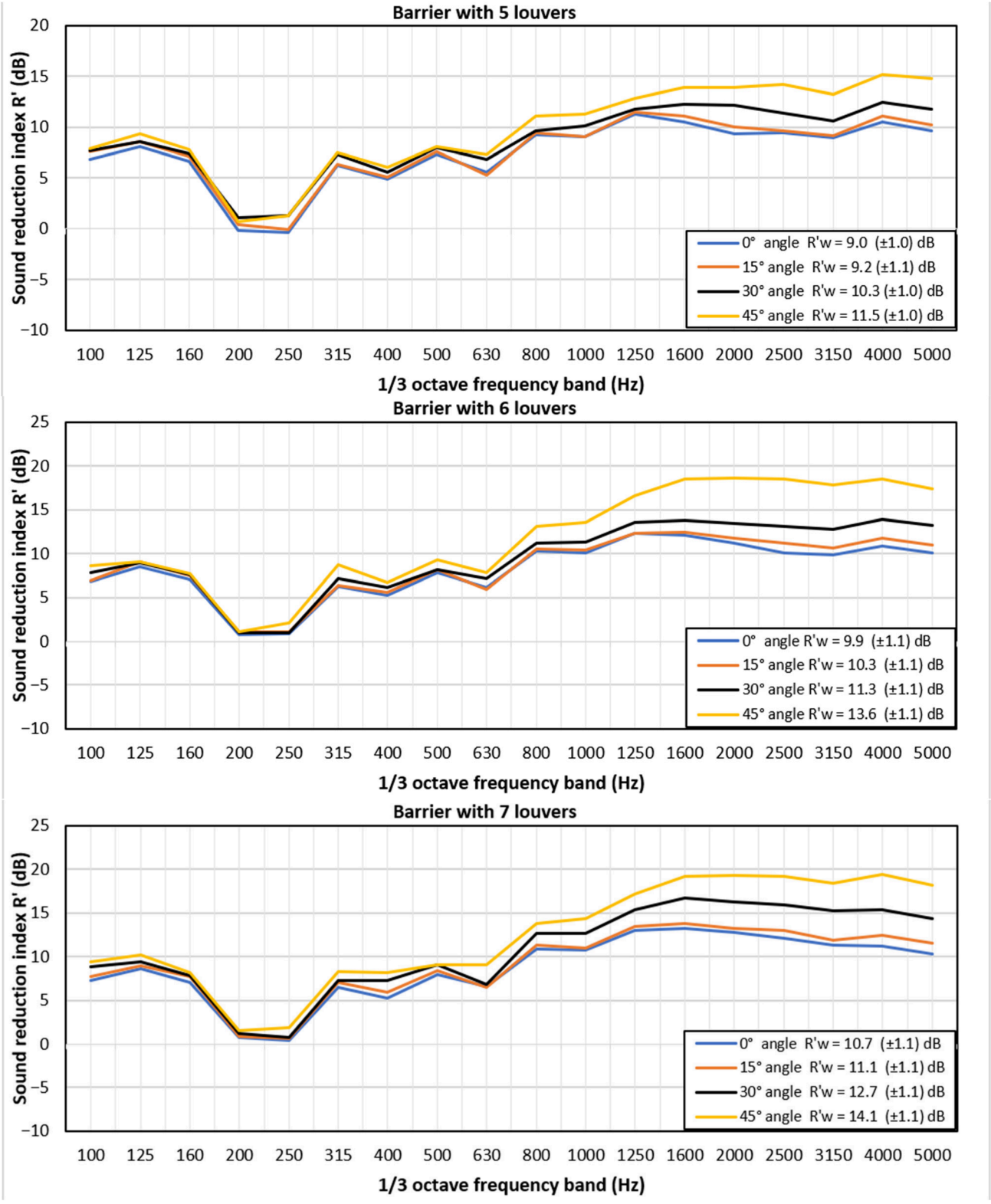

Figure 16. Apparent sound reduction index (R′) and weighted sound reduction index (R′w) results for the barriers with 200 kg/m^3 BHF.

3.3. Equivalent Sound Level Loss for the Louvered Noise Barriers

Figure 17 presents the equivalent sound level loss (LAeq) results for the louvered noise barriers with varying BHF densities.

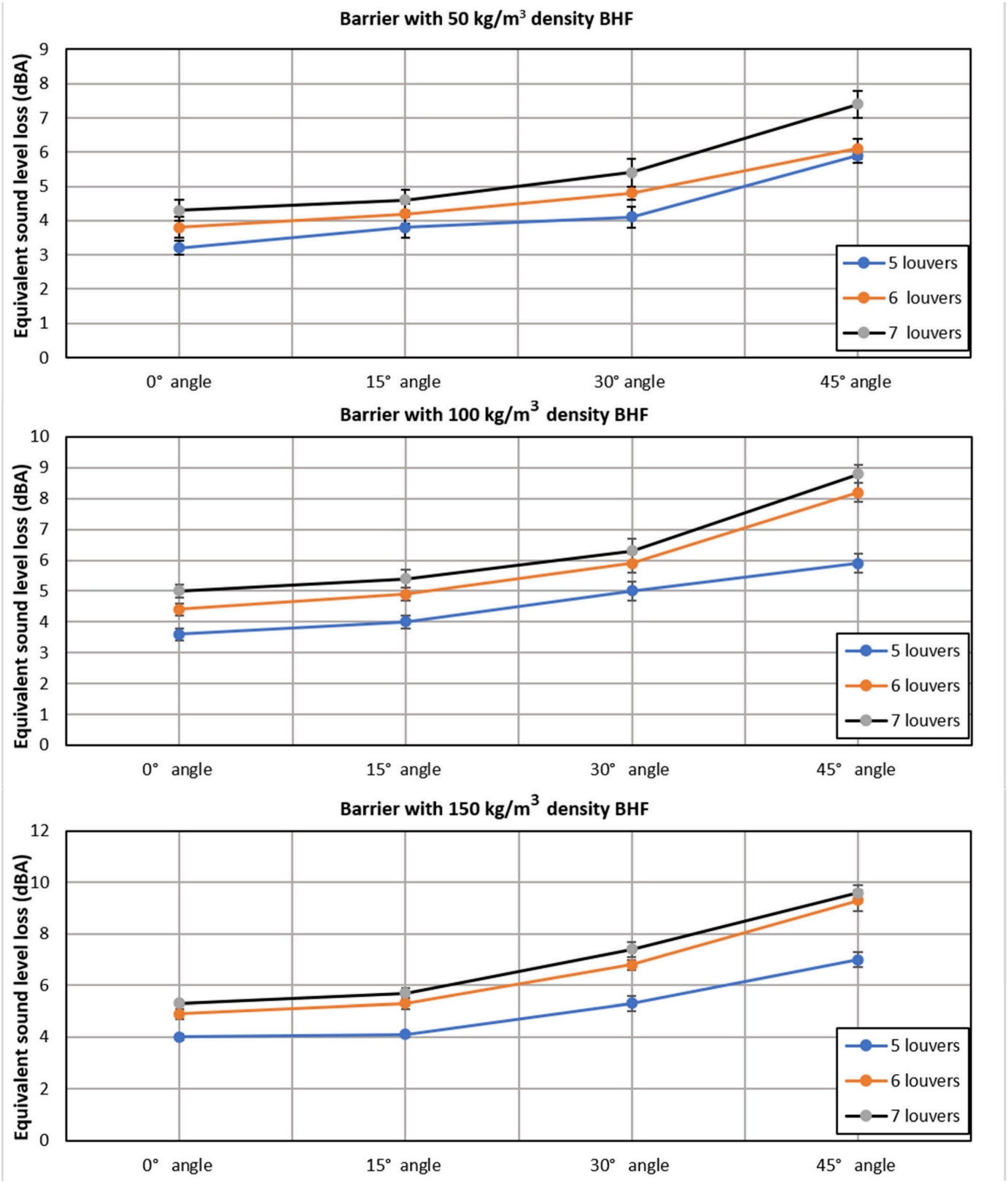

Figure 17. *Cont.*

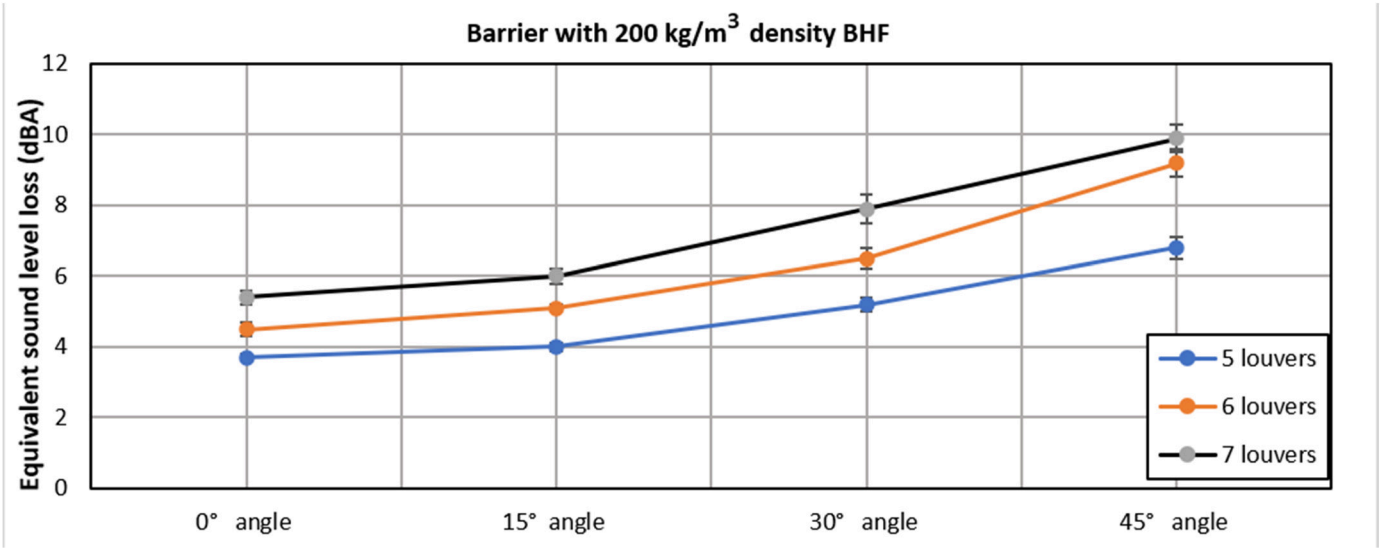

Figure 17. Equivalent sound level loss (LAeq) results for the structures with varying BHF densities.

The results show that the equivalent sound level loss (LAeq) for five-louver barriers with 50 kg/m^3 density BHF ranged from 3.2 dB (A) at a 0-degree louver angle to 5.9 dB (A) at a 45-degree angle. When six louvers were used, the result varied from 3.8 to 6.1 dB (A) and, when seven louvers were used, the values ranged from 4.3 to 7.4 dB (A). When the louvers in the noise-reducing barrier were filled with 100 kg/m^3 density BHF, the LAeq value ranged from 3.6 to 5.9 dB (A) with five louvers, from 4.4 to 8.2 dB (A) with six louvers, and from 5.0 to 8.8 dB (A) with seven louvers. When increasing the density of the fiber used in the louvers, regardless of their angle of inclination, the LAeq values increased, up to a density of 150 kg/m^3. At this density, the peak LAeq ranged from 4.0 dB (A) at a 0-degree angle of inclination of the louvers to 7.0 dB (A) at a 45-degree angle when five louvers were used in the barrier. When six louvers were used, the result ranged accordingly from 4.9 to 9.3 dB (A) and, when seven louvers were used, the values ranged from 5.3 to 9.6 dB (A). Similar results were observed when analyzing the barriers with a density of 200 kg/m^3 BHF: the LAeq ranged from 3.7 to 6.8 dB (A) with five louvers, from 4.5 to 9.2 dB (A) with six louvers, and from 5.4 to 9.9 dB (A) with seven louvers. The results demonstrate that the greatest influence on the LAeq was observed when turning the louvers from a 30-degree angle to 45 degrees, as well as when changing the number of louvers from five to six. It was also found that, when increasing the BHF density from 50 to 200 kg/m^3, the maximum LAeq value obtained when seven louvers turned to a 45-degree angle were used increased from 7.4 dB (A) to 9.9 dB (A). In all cases, regardless of the number of louvers and the fiber density used, increasing the angle of inclination of the louvers increased the equivalent sound level loss. The value generally increased when increasing the number of louvers and the density of the hemp fibers in them.

4. Discussion

Based on the presented research methodology, a prototype louvered noise barrier was manufactured and its acoustic parameters were investigated in a semi-anechoic noise reduction chamber. These parameters included the apparent sound reduction index (R′), weighted sound reduction index (Rw), insertion loss (IL), and equivalent sound level loss (LAeq). Based on the results, several key insights can be defined. First, in the mid-frequency range, in all cases, a sharp increase in the results was observed at 1000 Hz. At this frequency, the acoustic wavelength in air is approximately 0.34 m, which is comparable with the characteristic dimensions of the louvered barrier. As the wavelength comes

closer to the dimensions of the structure, the interaction between the sound wave and the barrier becomes more significant. Consequently, sound reflections between the louvers and energy dissipation within the hemp fiber filling become more pronounced, resulting in increased sound attenuation. At this frequency, increases in the assessed parameters begin to be seen, revealing the direct influence of the louver inclination angle on the results. At frequencies lower than 1000 Hz, the values were low in all cases and essentially similar, as the barrier structure has a poor ability to absorb the long wavelengths characteristic of low frequencies. For this reason, the direct influence of the louver inclination angle cannot be clearly observed in the low-frequency range. Similar observations have been reported in other studies conducted in semi-anechoic chambers [46].

In addition to the effects of the critical frequency and the angle of inclination of the louvers, the effectiveness of the louvered noise barrier can be explained by other acoustic phenomena, such as diffraction, viscous losses, tortuosity, and airflow resistivity. Inclination of the louvers at a certain angle creates conditions promoting multiple reflections and diffraction of sound waves in the air gaps between them, which lengthens the effective path of sound wave propagation and increases energy losses. By increasing the inclination angle of the louvers, the air gap between the louvers decreases while the amount of sound wave reflections increases; this leads to greater diffraction and energy losses, as a result of which the noise reduction performance of the barrier increases.

The hemp fiber inside the louvers, which is classified as a porous sound-absorbing material, also plays a significant role in determining the performance of the designed barrier. From the obtained results, it can be concluded that the optimal porosity of hemp fiber is achieved at a density of 100 kg/m^3, where not only are the sound absorption peaks reported in previous studies attained, but also the maximum efficiency of the structure itself in suppressing sound. The porosity of hemp fiber affects the attenuation of sound wave energy due to viscous and thermal losses, which is influenced by the interaction of air particles with the complex pore structure in the material. The barrier efficiency is determined not only by the airflow resistance of hemp fiber, but also by the tortuosity of the fibrous material, which increases the path of sound waves in the porous medium and promotes greater energy dissipation. Considering the influence of the described parameters on the efficiency of the structure, the described properties of hemp fiber should be evaluated and experimentally investigated in future studies.

Another important aspect identified in this study is related to the acoustic and physical characteristics of the louver filling. When studying the sound reduction index (R′) and sound insertion loss (IL) results, the peak values were determined for the barriers consisting of louvers filled with bleached hemp fiber with a density of 100 kg/m^3. When assessing those with higher density hemp fiber (i.e., 150 and 200 kg/m^3), the peak values decreased. Notably, when studying the 200 kg/m^3 louvers, the results became essentially similar to those obtained with the barriers filled with 50 kg/m^3 hemp fiber. This can be explained by the fact that, according to [40], increasing the density of hemp fiber increases its air resistance (50 kg/m^3—23.5 kPa·s/m^2; 100 kg/m^3—70.8 kPa·s/m^2; 150 kg/m^3—128.0 kPa·s/m^2; 200 kg/m^3—212.5 kPa·s/m^2). At the same time, although the insulating properties of the fiber increased over the entire frequency range, the sound absorption properties in the high-frequency range decreased slightly while increasing in medium- and low-frequency ranges, as a result of which a decrease in the peak efficiency of the structure at high frequencies was observed with increasing fiber density. However, it is worth noting that the use of higher density fiber allows for increased efficiency of the structure in attenuating sound in the low- and medium-frequency ranges, as reflected by increases in the weighted sound reduction index (R′w) and equivalent sound level loss (LAeq). After analyzing the obtained results, it can be concluded that to achieve higher

efficiency in the higher frequency range (from 1250 to 5000 Hz), it is recommended to use louvers filled with bleached hemp fiber with a density of 100 kg/m^3; meanwhile, to improve attenuation in the low- and medium-frequency ranges, a denser (i.e., 200 kg/m^3) hemp fiber should be used.

Higher fiber density reduces performance at high frequencies due to the sound absorption mechanisms in porous fibrous materials. This can be explained by the fact that, in general, the acoustic characteristics of hemp fibers are determined by the interactions between airborne sound waves and the pores of the material. When increasing the density of the investigated hemp fiber, the size of the pores in the fibrous material decreases, thus decreasing the porosity and increasing the airflow resistivity. While higher airflow resistance often improves a material's ability to dissipate sound energy in the low- and mid-frequency ranges, excessive resistance can prevent high-frequency sound waves from penetrating the porous structure. In the high-frequency range, as sound wave attenuation is caused by viscosity and thermal losses within the pores of the material, sound waves must be able to enter and propagate through the pore network. When the fiber density becomes too high, the surface of the material becomes more reflective than sound-absorbing. Therefore, a greater proportion of the energy of a sound wave traveling through a material is reflected, rather than scattered and absorbed within the material. This explains the decreased insertion loss (IL) and apparent sound reduction index (R′) values observed in the high-frequency range results. Considering the obtained results, a hemp fiber density of 100 kg/m^3 provides optimal airflow resistance, sound absorption, and adequate pore accessibility for high-frequency sound waves. When the density is increased to 150 or 200 kg/m^3, the acoustic characteristics shift towards lower and medium frequencies, which explains the determined increases in the weighted sound reduction index (R′w) and the equivalent sound level loss (LAeq), despite the fact that the maximum attenuation values decreased at frequencies between 1250 and 5000 Hz.

The greatest influence on the louvered barrier's sound attenuation efficiency was observed when the inclination of the louvers was turned from 30 degrees to 45 degrees, as well as when the number of louvers increased from five to six. In all cases, regardless of the number of louvers and the fiber density used, increasing the angle of inclination of the louvers increased the noise attenuation properties of the barrier, which can be attributed to narrowing of the air gap between the louvers. The measured values generally increased when increasing the number of louvers and the density of hemp fibers in them. This can be attributed to an increase in the surface area and amount of material interacting with the propagating sound wave, resulting in greater sound wave energy loss and increased attenuation.

When assessing the feasibility of using hemp fiber in this design, it is useful to compare the obtained results with those of other studies. For example, compared with the results reported in [15], where the louvers were covered with mineral wool (the density of which reached 40 kg/m^3) at a thickness on both sides of the louvers of 20 mm, the equivalent sound level reduction reached up to about 11 dB (A), which is similar to the 9.9 dB (A) reduction obtained in our study (approximately 10% lower than the value reported in [15]). Our slightly lower result may be influenced by the fact that the authors of [15] used a structure with louvered panels with a total thickness of about 40 mm, while ours was only 30 mm thick. It is also worth mentioning the environmental friendliness and sustainability advantages of the louvered noise barrier with hemp fiber, when compared with mineral wool. Furthermore, the barrier investigated in this study is superior in that its louvered structure is protected from environmental conditions, compared with the previous studies, in which the louvered panels were used without a frame and the sound-absorbing material was simply glued to the metal plates.

As mentioned in the Introduction, considering the increasing popularity of louvered noise barriers filled with rubber panels or granulate, to comparatively evaluate the advantages of hemp fiber, the louvered barrier described in this study was filled with rubber granulate panels and loose rubber granulate. Analogous studies were conducted according to the described methodology, and the results have been presented in [46]. The obtained results allowed us to evaluate the noise reduction efficiency of the same structure when using different fillers. It was found that the maximum insertion loss of the comparative structure reached 12.63 dB at 2500 Hz, the apparent sound reduction index reached up to about 10 dB, and the equivalent noise level reduction reached up to 9.3 dB (A). These results confirm the advantages of hemp fiber when used in this type of louvered structure. The peak values obtained for the louvered noise barriers filled with hemp fiber of varying densities are summarized in Table 1.

Table 1. Summarized results of louvered noise barriers with BHF of varying densities tested in the noise reduction chamber.

Fiber Density, kg/m^3	Number of Louvers	Louver Inclination Angle			
		0°	**15°**	**30°**	**45°**
Sound Insertion Loss (IL), dB					
50	5	5.85	6.09	6.47	9.44
	6	7.78	8.00	8.78	12.27
	7	8.33	8.53	9.53	14.77
100	5	7.02	7.29	8.27	9.67
	6	8.98	9.35	11.22	16.89
	7	10.67	10.55	11.38	18.13
150	5	7.08	7.13	8.62	10.53
	6	8.39	8.86	10.84	15.88
	7	9.76	9.89	11.72	16.6
200	5	6.25	6.64	7.87	9.48
	6	7.65	7.94	9.39	14.05
	7	8.75	9.31	12.3	14.76
Apparent Sound Reduction index (R′), dB					
50	5	10.3	11.1	12.4	15.4
	6	12.2	12.4	13.2	17.1
	7	13.2	13.4	14.4	19.7
100	5	12.1	12.4	12.7	14.5
	6	13.4	13.8	15.7	21.3
	7	15.1	15.0	15.8	23.0
150	5	12.2	12.2	13.1	15.2
	6	13.4	13.4	15.3	20.3
	7	14.2	14.3	16.2	21.1
200	5	11.3	11.5	12.5	15.2
	6	12.3	12.4	13.9	18.6
	7	13.2	13.8	16.7	19.4

Table 1. *Cont.*

Fiber Density, kg/m^3	Number of Louvers	Louver Inclination Angle			
		0°	**15°**	**30°**	**45°**
Weighted Sound Reduction Index (R′w)					
50	5	8.3	8.9	9.0	10.5
	6	8.9	9.3	9.6	10.7
	7	9.5	9.6	10.2	11.5
100	5	9.0	9.3	10.0	10.8
	6	9.9	10.1	10.9	12.6
	7	10.4	10.6	11.2	12.9
150	5	9.5	9.5	10.3	11.8
	6	10.3	10.6	11.7	13.7
	7	10.7	10.8	12.1	13.1
200	5	9.0	9.2	10.3	11.5
	6	9.9	10.3	11.3	13.6
	7	10.7	11.1	12.7	14.1
Equivalent Sound Level Loss (LAeq)					
50	5	3.2	3.8	4.1	5.9
	6	3.8	4.2	4.8	6.1
	7	4.3	4.6	5.4	7.4
100	5	3.6	4.0	5.0	5.9
	6	4.4	4.9	5.9	8.2
	7	5.0	5.4	6.3	8.8
150	5	4.0	4.1	5.3	7.0
	6	4.9	5.3	6.8	9.3
	7	5.3	5.7	7.4	9.6
200	5	3.7	4.0	5.2	6.8
	6	4.5	5.1	6.5	9.2
	7	5.4	6.0	7.9	9.9

Considering the results obtained in this study, from a practical application perspective, the developed louvered noise barrier demonstrates potential for implementation in noise control solutions where acoustic attenuation and high airflow permeability are required. Based on the measured acoustic performance, the proposed design may be suitable for HVAC systems, ventilation units, heat pumps, and power generators, which typically emit significant noise in the medium- and high-frequency ranges. The scalability of the concept is supported by the modular nature of the louvered structure, as the number, dimensions, and inclination angle of the louvers can be adapted to meet specific airflow and acoustic requirements while maintaining the same operating principle, indicating that the proposed barrier can be transferred from laboratory-scale prototypes to full-scale engineering applications. Before implementing the barrier, the frequency characteristics of the sound emitted by the device should be evaluated, as this type of noise barrier most effectively suppresses sound in the medium- and high-frequency range, with peak suppression achieved in the frequency range of 1250–2500 Hz. Depending on practical requirements, the inclination angle and number of louvers can be changed, thus increasing or decreasing the air permeability. The proposed barrier is suitable for reducing noise

emitted by heat pumps, generators, or ventilation equipment, as diffusers typically produce sounds in the high-frequency range (generally in the range of 500–8000 Hz, but also up to 20,000 Hz) [3,7]. Meanwhile, the noise generated by generators is due to the operation of their exhaust pipe, AVR panel, and radiator, and is typically characterized by high frequencies (2000–8000 Hz) associated with internal combustion processes [9,10]. The studied louvered noise barrier, due to its structural features, can be used in outdoor and indoor installations. To improve the reliability of the barrier in outdoor conditions, the hemp fiber's water and moisture resistance, weathering resistance, fire resistance, and biotic resistance should be evaluated in future works with the aim of improving its resistance. To improve these parameters, methods such as alkali, silane, chemical impregnation, salicylic acid, or natural monoterpene phenol treatments could be considered [43–45].

Limitations

This study has several limitations. The acoustic efficiency of the louvered noise-absorbing barrier was evaluated in a semi-anechoic chamber, examining typical parameters such as the apparent sound reduction index (R′), weighted sound reduction index (Rw), insertion loss (IL), and equivalent sound level loss (LAeq). These experiments are comparable with laboratory conditions, and thus, may not fully reflect the effectiveness of such a barrier in real conditions. Standing waves may form in a semi-anechoic chamber of this size, potentially affecting the results. It is also worth noting that the studied structure was designed and manufactured taking the parameters of the acoustic chamber into account; therefore, it was not possible to assess the effects of varying the width, thickness, or length of the louver on sound attenuation. It is also unclear how the barrier's effectiveness will change under changing environmental conditions (e.g., humidity, temperature), and whether applying this design to reduce noise in real conditions may increase the sound level due to vibration generated by the equipment during operation. Although care was taken to ensure proper installation of the prototype, the potential effects of edge leakage and frame vibrations on the measured acoustic performance cannot be completely excluded. In addition, the airflow resistance and ventilation performance of the developed louvered barrier were not evaluated in the present study. All these aspects should be evaluated in future studies, through the use of numerical modeling and/or testing the barrier in real conditions.

5. Conclusions

In this study, the acoustic properties of a louvered noise barrier containing bleached hemp fiber were investigated. After designing the noise barrier, a prototype which fully met the design parameters was constructed and tested in a semi-anechoic noise reduction chamber. Barrier configurations with five, six, or seven louvers were tested. The louvers were rotated at 0, 15, 30, or 45 degrees, and the density of the hemp fiber in the louver was varied from 50 to 200 kg/m^3 (in steps of 50 kg/m^3). The apparent sound reduction index (R′), insertion loss (IL), and equivalent sound level loss (LAeq) were measured.

The highest apparent sound reduction index (R′) was 23.0 dB and the highest insertion loss (IL) was 18.3 dB, determined for the barrier consisting of seven louvers filled with 100 kg/m^3 bleached hemp fiber. The highest weighted sound reduction index (R′w) of 14.1 dB and the highest equivalent sound level loss (LAeq) were determined when testing the barrier consisting of seven louvers filled with 200 kg/m^3 bleached hemp fiber. In all cases, the highest values were determined when the louver inclination angle was set at 45 degrees with respect to the noise source. The peak values were most often determined in the high-mid- and high-frequency ranges, specifically at frequencies of 1600, 2000, and 2500 Hz. It was found that increasing the hemp fiber density increased the sound attenuation properties of the structure in the low- and medium-frequency ranges but

decreased them in the high-frequency range, where peaks were detected in most cases. It was also found that the greatest influence on the efficiency of the structure in attenuating sound was observed when the louver inclination angle was changed from 30 to 45 degrees, and the number of louvers changed from six to seven.

To reduce the noise generated by devices that require high air permeability during operation, it is recommended to use the barrier structure studied in this work with seven louvers turned at an angle of 45 degrees. To reduce the equivalent noise level, it is recommended to fill the louvers with bleached hemp fiber, at a density up to 200 kg/m^3. If it is necessary to reduce only high-frequency noise (e.g., in the range of 1600–2500 Hz), it is recommended to implement a barrier consisting of louvers filled with bleached hemp fiber at a density of 100 kg/m^3.

From a practical perspective, the developed louvered hemp fiber noise barrier demonstrates potential for application in installations including HVAC systems, air-source heat pumps, ventilation units, and power generators, for which noise reduction and high airflow permeability are required. The results indicate that the designed barrier is particularly effective in attenuating noise in the medium- and high-frequency ranges. Furthermore, the measured equivalent sound level reduction ranged from 3.2 to 9.9 dB (A), while the best-performing configurations achieving reductions of 8.2–9.9 dB (A), which are within the 5–10 dB noise reduction range recommended for noise barriers installed near heat pump systems [12]. Based on the obtained results, configurations incorporating 6–7 louvers inclined at 45° and filled with hemp fiber at a density of 100 kg/m^3 are recommended for applications requiring effective noise reduction and high airflow permeability. Although the presented results indicate that the proposed barrier may provide acoustically meaningful noise mitigation in residential environments, it should be noted that the present study was conducted under controlled laboratory conditions using a prototype-scale barrier tested in a semi-anechoic chamber. Therefore, additional full-scale field investigations are required to evaluate the effects of environmental conditions, installation configuration, airflow regimes, and long-term exposure on the acoustic performance and durability of the proposed barrier.

Future research plans include assessing the impacts of the structural parameters of the louvered noise barrier on sound attenuation using numerical modeling tools, as well as determining the aerodynamic parameters of the structure.

6. Patents

Based on this work, patent No. 7182 "Louvered noise barrier with hemp fibre" was prepared and issued by The State Patent Bureau of the Republic of Lithuania on 10 February 2026.

Author Contributions: Conceptualization, E.S. and T.J.; methodology, E.S.; software, E.S.; validation, E.S. and T.J.; formal analysis, E.S.; investigation, E.S.; resources, T.J.; data curation, T.J.; writing—original draft preparation, E.S.; writing—review and editing, T.J.; visualization, E.S.; supervision, T.J.; project administration, T.J.; funding acquisition, T.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Research details can be provided upon request to the corresponding author.

Acknowledgments: We would like to thank the VILNIUS TECH Institute of Environmental Protection for access to the semi-anechoic sound-absorbing chamber.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviation is used in this manuscript:

BHF	Bleached hemp fiber
EEA	European Environment Agency
HVAC	Heating, Ventilation, and Air Conditioning
IEC	International Electrotechnical Commission
IL	Insertion Loss
ISO	International Organization for Standardization

References

1. European Environment Agency. *Environmental Noise in Europe 2025*; EEA Report No 05/2025; European Environment Agency: Copenhagen, Denmark, 2025. Available online: https://www.eea.europa.eu/publications/environmental-noise-in-europe-2025 (accessed on 1 May 2026).
2. Imhof, M.; Henning, N.; Kreft, S. Effects of background noise on cognitive performance in elementary school children. *List. Educ.* **2009**, *2*, 1–10.
3. Ouis, D.; Hassanain, M.A.; Alshibani, A.; Ghaithan, A.M. Noise from heating, ventilation, and air conditioning (HVAC) systems: A review of its characteristics, effects and control. *J. Build. Eng.* **2025**, *112*, 113770. [CrossRef]
4. Erickson, L.C.; Newman, R.S. Influences of background noise on infants and children. *Curr. Dir. Psychol. Sci.* **2017**, *26*, 451–457. [CrossRef] [PubMed]
5. Acun, V.; Graetzer, S.; Radivan, M.; Torija, A.J. Human response to air source heat pump noise: Influence of background noise and source characteristics on soundscape quality. *Acta Acust.* **2026**, *10*, 32. [CrossRef]
6. Acun, V.; Barton, L.S.; Cox, T.; Graetzer, S.; Hargreaves, J.; Radivan, M.; Torija Martinez, A.J.; Waddington, D.; Wong-McSweeney, D. Evaluating human response to air source heat pump noise for sustainable domestic heating. In Proceedings of the Acoustics 2024, Larnaca, Cyprus, 18–20 September 2024. [CrossRef] [PubMed]
7. Sikora, R.; Wagnerová, L.; Landryová, J.; Šíma, S.; Wrona, S. Influence of environmental noise on quality control of HVAC devices based on convolutional neural network. *Appl. Sci.* **2021**, *11*, 7484. [CrossRef]
8. Determination of Noise Pollution Levels Caused by Diesel Generators: A Case Study at the MTU University Complex. Available online: https://www.researchgate.net/publication/398421864_Determination_of_Noise_Pollution_Levels_Caused_by_Diesel_Generators_A_Case_Study_at_the_MTU_University_Complex (accessed on 1 May 2026).
9. Giwa, S.O.; Nwaokocha, C.N.; Adeyemi, H.O. Noise and emission characterization of off-grid diesel-powered generators in Nigeria. *Manag. Environ. Qual. Int. J.* **2019**, *30*, 783–802. [CrossRef]
10. Giwa, S.O.; Nwaokocha, C.N.; Osifeko, O.M.; Orogbade, B.O.; Taziwa, R.T.; Dyantyi, N.; Sharifpur, M. Appraising machine learning algorithms in predicting noise level and emissions from gasoline-powered household backup generators. *Int. J. Environ. Sci. Technol.* **2025**, *22*, 3071–3088.
11. Liu, D.; Feng, Y.; Jia, J.; Si, P.; Feng, Y. The noise spectral characteristics and noise reduction schemes of screw air-source heat pump: A case study. *Build. Simul.* **2024**, *17*, 53–70. [CrossRef]
12. Reichl, C.; Wagner, P.; Blank-Landeshammer, B.; Sporr, A.; Pedersen, S.; Wagner, S. *Report on Heat Pump Installation with Special Focus on Acoustic Impact*; IEA Heat Pumping Technologies Annex 51: Acoustic Signatures of Heat Pumps; IEA HPT: Vienna, Austria, 2021. Available online: https://heatpumpingtechnologies.org/annex51/ (accessed on 13 June 2026).
13. Dimitrijević, S.M.; García-Chocano, V.M.; Cervera, F.; Roth, E.; Sánchez-Dehesa, J. Sound insulation and reflection properties of sonic crystal barrier based on micro-perforated cylinders. *Materials* **2019**, *12*, 2806. [CrossRef] [PubMed]
14. Lee, J.; Chang, J.D.; Coffeen, R. Acoustical evaluations of a double skin façade as a noise barrier of a naturally ventilated façade. *J. Acoust.* **2020**, *2*, e200001. [CrossRef]
15. Astrauskas, T.; Baltrėnas, P.; Januševičius, T.; Grubliauskas, R. Louvred noise barrier for traffic noise reduction. *Balt. J. Road Bridge Eng.* **2021**, *16*, 140–154. [CrossRef]
16. Shima, H.; Murase, M.; Tomita, N.; Iida, K. Noise Reducing Apparatus. U.S. PatentUS5168130A, 1 December 1992. Available online: https://patents.google.com/patent/US5168130A/en (accessed on 1 May 2026).
17. da Silva, E.B.V. Evaluation of the Acoustical Performance of Louvre by Impulse Response Analysis. Ph.D. Thesis, Programa de Pós-Graduação em Engenharia Mecânica, Centro Tecnológico, Universidade Federal de Santa Catarina, Florianópolis, Brazil, 1998.
18. Viveiros, E.B.; Gibbs, B.M.; Gerges, S.N.Y. Measurement of sound insulation of acoustic louvres by an impulse method. *Appl. Acoust.* **2002**, *63*, 1301–1313. [CrossRef]
19. Maciel, M.A.; Duarte, M.A.V. Analytical modelling of active acoustic louvres. In Proceedings of the International Congress on Sound and Vibration (ICSV), Beijing, China, 13–17 July 2014.

20. Martello, N.Z.; Fausti, P.; Santoni, A.; Secchi, S. The use of sound absorbing shading systems for the attenuation of noise on building façades: An experimental investigation. *Buildings* **2015**, *5*, 1346–1360. [CrossRef]
21. Vilniškis, T.; Baltrėnas, P.; Januševičius, T. Case study: Evaluation of noise reduction in frequencies and sound reduction index of construction with variable noise isolation. *Noise Control Eng. J.* **2020**, *68*, 199–208. [CrossRef]
22. Liu, Z.; Zhan, J.; Fard, M.; Davy, J.L. Acoustic properties of multilayer sound absorbers with a 3D printed micro-perforated panel. *Appl. Acoust.* **2017**, *121*, 25–32. [CrossRef]
23. Asdrubali, F.; Schiavoni, S.; Horoshenkov, K.V. A review of sustainable materials for acoustic applications. *Build. Acoust.* **2012**, *19*, 283–311. [CrossRef]
24. Berardi, U.; Iannace, G. Acoustic characterization of natural fibers for sound absorption applications. *Build. Environ.* **2015**, *94*, 840–852. [CrossRef]
25. Rezaieyan, E.; Taban, E.; Berardi, U.; Mortazavi, S.B.; Faridan, M.; Mahmoudi, E. Acoustic properties of natural fiber reinforced composite micro-perforated panel (NFRC-MPP) made from cork fiber and polylactic acid (PLA) using 3D printing. *J. Build. Eng.* **2024**, *84*, 108491. [CrossRef]
26. Iannace, G. The acoustic characterization of green materials. *Build. Acoust.* **2017**, *24*, 101–113. [CrossRef]
27. Zimniewska, M. Hemp fibre properties and processing for textile applications: A review. *Materials* **2022**, *15*, 1901. [CrossRef] [PubMed]
28. Rehman, M.; Fahad, S.; Du, G.; Cheng, X.; Yang, Y.; Tang, K.; Liu, L.; Liu, F.H.; Deng, G. Evaluation of hemp (*Cannabis sativa* L.) as an industrial crop: A review. *Environ. Sci. Pollut. Res.* **2021**, *28*, 52832–52843. [CrossRef] [PubMed]
29. Scrucca, F.; Ingrao, C.; Maalouf, C.; Moussa, T.; Polidori, G.; Messineo, A.; Arcidiacono, C.; Asdrubali, F. Energy and carbon footprint assessment of production of hemp hurds for application in buildings. *Environ. Impact Assess. Rev.* **2020**, *84*, 106417. [CrossRef]
30. Arehart, J.H.; Nelson, W.S.; Srubar, W.V. On the theoretical carbon storage and carbon sequestration potential of hempcrete. *J. Clean. Prod.* **2020**, *266*, 121846. [CrossRef]
31. Gumanová, V.; Sobotová, L.; Dzuro, T.; Badida, M.; Moravec, M. Experimental Survey of the Sound Absorption Performance of Natural Fibres in Comparison with Conventional Insulating Materials. *Sustainability* **2022**, *14*, 4258. [CrossRef]
32. Hemp Production in the EU—European Commission. Available online: https://agriculture.ec.europa.eu/farming/crop-productions-and-plant-based-products/hemp_en (accessed on 13 June 2026).
33. Liao, J.; Zhang, S.; Tang, X. Sound Absorption of Hemp Fibres (*Cannabis Sativa* L.) Based Nonwoven Fabrics and Composites: A Review. *J. Nat. Fibres* **2020**, *19*, 1297–1309. [CrossRef]
34. Santoni, A.; Bonfiglio, P.; Fausti, P.; Marescotti, C.; Mazzanti, V.; Mollica, F.; Pompoli, F. Improving the sound absorption performance of sustainable thermal insulation materials: Natural hemp fibres. *Appl. Acoust.* **2019**, *150*, 279–289. [CrossRef]
35. Zhang, C.; Li, H.; Gong, J.; Chen, J.; Li, Z.; Li, Q.; Cheng, M.; Li, X.; Zhang, J. The review of fibre-based sound-absorbing structures. *Text. Res. J.* **2023**, *93*, 434–449. [CrossRef]
36. Zhang, D.; Zhou, X.; Gao, Y.; Lyu, L. Structural Characteristics and Sound Absorption Properties of Waste Hemp Fibre. *Coatings* **2022**, *12*, 1907. [CrossRef]
37. Farid, M.; Purniawan, A.; Diah, S.; Pratiwi, V.M.; Yoessa, M.I. High sound absorption of polyester composites/fibre hemp/nanocellulose for automotive interior materials. *Mater. Int.* **2020**, *2*, 170–174. [CrossRef]
38. Dragonetti, R.; Napolitano, M.; Boccarusso, L.; Durante, M. A study on the sound transmission loss of a new lightweight hemp/bio-epoxy sandwich structure. *Appl. Acoust.* **2020**, *167*, 107379. [CrossRef]
39. Dahal, R.K.; Acharya, B.; Dutta, A. Mechanical, thermal, and acoustic properties of hemp and biocomposite materials: A review. *J. Compos. Sci.* **2022**, *6*, 373. [CrossRef]
40. Strazdas, E.; Januševičius, T. Evaluating hemp fibre as a sustainable bio-based material for acoustic applications. *Sustainability* **2026**, *18*, 741. [CrossRef]
41. Filazi, A.; Akat, R.; Pul, M.; Tortuk, S.; Özdin, A. Physical structural mechanical and thermal insulation properties of hemp fiber-substituted geopolymer composites. *Materials* **2025**, *18*, 2536. [CrossRef] [PubMed]
42. Filazi, A.; Tortuk, S.; Pul, M. Determination of optimum blast furnace slag ash and hemp fiber ratio in cement mortars. *Structures* **2023**, *57*, 105024. [CrossRef]
43. Feng, F.; Wei, H.; Xiao, Y.; Berardi, U.; Quaranta, G.; Demartino, C. Bio-based insulation materials in sustainable constructions: A review of environmental, thermal and acoustic insulation, durability, and mechanical performances. *Renew. Sustain. Energy Rev.* **2025**, *223*, 115872. [CrossRef]
44. Alao, P.F.; Press, R.; Ruponen, J.; Mikli, V.; Kers, J. Influence of protic ionic liquid-based flame retardant on the flammability and water sorption of alkalized hemp fibre-reinforced PLA composites. *Polymers* **2023**, *15*, 3661. [CrossRef] [PubMed]
45. Donatelli, A.; Cuna, D.; Tagliente, M.A.; Protopapa, M.L.; Mevoli, A.; Aversa, P.; Blasi, C.; Capodieci, L.; Luprano, V.A.M. Effect of treatments on the aging behaviour of hemp fibres for building construction in the Mediterranean Area. *J. Build. Eng.* **2017**, *11*, 37–47. [CrossRef]

46. Strazdas, E.; Januševičius, T. Acoustic properties of a louvered noise barrier with tire rubber granulate infill. In Proceedings of the Forum Acusticum/EuroNoise 2025, Session A01.07/A08.06 "Innovative Noise Barriers to Enhance Acoustic Comfort", Málaga, Spain, 23–26 June 2025; pp. 175–180. [CrossRef]
47. *ISO 10534-2:2023*; Acoustics—Determination of Sound Absorption Coefficient and Impedance in Impedance Tubes—Part 2: Transfer-Function Method. ISO: Geneva, Switzerland, 2023.
48. *ASTM E2611-17*; Standard Test Method for Normal Incidence Determination of Porous Material Acoustical Properties Based on the Transfer Matrix Method. ASTM International: West Conshohocken, PA, USA, 2017.
49. *ISO 10140-4:2021*; Acoustics—Laboratory Measurement of Sound Insulation of Building Elements—Part 4: Measurement Procedures and Requirements. ISO: Geneva, Switzerland, 2021.
50. *IEC 61672*; Electroacoustics–Sound Level Meters. International Electrotechnical Commission (IEC): Geneva, Switzerland, 2013.
51. *IEC 60651*; Sound Level Meters. International Electrotechnical Commission (IEC): Geneva, Switzerland, 1979.
52. *IEC 60804*; Integrating-Averaging Sound Level Meters. International Electrotechnical Commission (IEC): Geneva, Switzerland, 2000.
53. *ISO 717-1*; Acoustics—Rating of Sound Insulation in Buildings and of Building Elements—Part 1: Airborne Sound Insulation. ISO: Geneva, Switzerland, 2020.
54. *ISO 11691:2020*; Acoustics—Measurement of Insertion Loss of Noise Barriers In Situ. ISO: Geneva, Switzerland, 2020.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.