Original Article

Journal of Occupational Health and Epidemiology
Journal Homepage: https://johe.rums.ac.ir/
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Rafsanjan University of Medical Sciences

Enhancing High-Frequency Bandwidth in MPP-Porous Material Composite Absorbers: A Numerical Simulation Approach for Optimal Parameter Selection

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Citation: SheikhMozafari MJ, Ahmadi Asour A, Hajinejad S. Enhancing High-Frequency Bandwidth in MPP-Porous Material Composite Absorbers: A Numerical Simulation Approach for Optimal Parameter Selection. J Occup Health Epidemiol. 2024;13(2):119-31.

Article Info

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Article history
Received: Nov 2023
Accepted: Apr 2024

10. 61186/johe.13.2.119

Print ISSN: 2251-8096
Online ISSN: 2252-0902

Peer review under responsibility of Journal of Occupational Health and Epidemiology

Abstract

Background: Porous absorbers are highly effective at attenuating high-frequency noise, yet they face inherent limitations, including reduced absorption at lower frequencies and vulnerability to environmental factors. Combining porous materials with Micro Perforated Panels (MPP) offers a solution but often sacrifices bandwidth. This study deals with optimizing parameters to extend the bandwidth toward higher frequencies, considering health concerns related to high-frequency noise exposure.
Materials & Methods: This study used Finite Element Numerical Simulation (FEM) in COMSOL to model a porous material and MPP composite. It examined parameters like material thickness, air gap, hole diameter, panel thickness, MPP perforation percentage, and layer configurations. The goal was to find the best configuration to expand bandwidth, selecting and fixing the most effective parameter at each stage.
Results: Findings from the simulated model aligned with direct impedance tube measurements. Enlargement of the fibrous material thickness, up to practical limits, expanded bandwidth. Optimizing MPP parameters involved minimizing hole diameter and panel thickness while maximizing perforations. The most effective layer configuration for bandwidth expansion consisted of an air layer, porous material, another air layer, additional porous material, and the MPP layer.
Conclusions: Careful parameter selection can significantly increase bandwidth and absorption coefficients at higher frequencies. The incorporation of MPP enhances the composite's overall resilience, offering mechanical strength, resistance to environmental factors, and aesthetic appeal. The high precision of FEM simulations positions them as a valuable alternative to direct measurements such as impedance tube assessments. This study provides a comprehensive approach to improving porous absorber performance.

Keywords: Noise, Porosity, Finite Element Analysis, Environmental Exposure

Introduction

Urban expansion, transportation growth, and industrial development have caused a significant increase in noise pollution, which is a major concern for experts [1, 2]. Noise pollution, defined as unpleasant sounds negatively affecting health, is a major environmental issue [3]. The World Health Organization (WHO) identifies noise levels above 65 dB as harmful, leading to various health issues such as hearing loss, stress, reduced concentration, and cardiovascular problems [4-7]. Methods such as using sound-absorbing materials along sound propagation paths can help control noise [8, 9]. Surface modifications and incorporation of sound-absorbing materials improve acoustic conditions within buildings [10]. Porous fibrous materials are the most prevalent sound-absorbing materials, categorized into two types of natural and synthetic fibers [11]. Although synthetic fibers such demonstrate high sound absorption efficiency, they pose environmental and health risks [10-13]. Consequently, researchers have shifted their attention to exploring natural materials with similar acoustic properties but less harmful effects. Many studies have investigated the acoustic performance of sound absorbers composed of natural fibers as promising substitutes for synthetic fibers, yielding encouraging results [14]. These natural fibers exhibited favorable acoustic behavior at medium and particularly high frequencies, displaying very high absorption coefficients at those frequencies [15-17].

In addition to their various advantages, such as biodegradability, cost-effective, and readily available, porous natural fiber absorbers demonstrate high absorption coefficients at medium (500 to 2000 Hz) and high frequencies (above 2000 Hz). However, they struggle with low absorption at low frequencies (below 50 Hz) as well as issues such as fiber particle separation leading to indoor pollution and health problems. This limits their use in settings such as food industries and hospitals where pollution is a concern. Additionally, they have low mechanical strength, poor resistance to temperature and humidity, and are prone to fungal and microbial growth [18-20].

Increasing the thickness of fiber absorbers can improve their absorption coefficient at low frequencies, but maintaining a thickness of $\lambda/4$ from the hard wall surface is crucial for optimal performance. However, achieving sufficient absorption at low frequencies would require impractical and space-consuming thicknesses, making it economically unviable [20]. To address these challenges comprehensively, researchers have been using microperforated panels (MPP) in various studies [11]. MPPs are thin rigid plates made from metals, wood, etc. MPP contains numerous small holes with sizes less than millimeters [10]. In a study by Beheshti et al., they explored the combination of different fiber absorbers with MPP to extend the bandwidth at frequencies below 3000 Hz. The study revealed that the combination of fiber absorbers and MPP led to increased bandwidth [11]. The same has also been mentioned in the study of Basirjafari et al. [3]. MPP absorbers offer several advantages, including high durability, aesthetic appeal, and environmentally friendly nature. Additionally, MPP absorbers allow for the setting of a specific resonance frequency within a certain range [21]. This resonance frequency determination means that when the frequency of sound impacting the MPP matches the inherent frequency of the MPP, the air columns within the MPP holes vibrate more intensely, resulting in a higher conversion of sound energy into heat [22]. In Hashemi et al.'s research, a combination of Kenaf fiber absorbers and MPP was utilized to enhance the absorption coefficient at frequencies below 2500 Hz. Their findings indicated that with accurate determination of the effective parameters, significant absorption improvements were achieved within this range [20]. Despite MPP absorbers being a favorable alternative to porous absorbers considering their mentioned advantages, they suffer from limitations such as lower absorption at high frequencies and a narrower absorption bandwidth compared to porous absorbers due to their flat and porous structure acting as Helmholtz absorbers [19]. Various studies have explored solutions to expand the bandwidth by altering MPP specifications, including adjusting the hole diameter, panel size, and perforation, as highlighted in previous research [11, 19, 20].

Incorporating filler materials such as fiber materials in the backspace of MPP absorbers is an alternative approach to enhance bandwidth, as mentioned in various studies [23, 24]. However, combining MPP with fiber absorbers may reduce overall performance at high frequencies and lower frequency bandwidth toward low frequencies [23, 25]. This is problematic for settings such as offices or industrial environments where high-frequency issues are common. The key challenge is maintaining porous absorbers' acoustic behavior at high frequencies when combined with MPP absorbers to achieve a suitable bandwidth covering a broad frequency range.

The acoustic performance of sound absorbers is quantified by the absorption coefficient, which ranges from 0 to 1, with higher values indicating better efficiency. The absorption coefficient can be measured through experimental methods, such as using an impedance tube, or through mathematical models known as predictive models. However, obtaining impedance tubes may be limited due to high costs or time constraints, prompting researchers to explore the use of mathematical models such as Johnson-Champoux-Allard (JCA), Delany-Bazley (DB), Miki, etc., as a cost-effective and time-saving alternative [20, 26].

Prior research has primarily focused on improving absorption at low frequencies and expanding bandwidth toward the lower range by combining porous fiber absorbers with MPP. However, maintaining optimal acoustic performance at high frequencies is crucial, especially in industrial environments where high-frequency noise can cause hearing loss. Unfortunately, many studies have overlooked this aspect. Thus, this study aims to investigate and optimize parameters influencing the acoustic behavior of a composite containing areca nut natural fiber and MPP absorber, with the goal of extending bandwidth toward higher frequencies.

To examine the acoustic behavior of this composite, numerical simulations utilizing the Finite Element

Method (FEM) and the 5-parameter JCA model were conducted in the COMSOL software version 6.1. The characteristics of the natural fibers used in this study were based on findings from a prior investigation conducted by Raj et al. [27]. This research seeks to contribute to the advancement of sound-absorbing materials with efficacy across a broader frequency range, particularly to address acoustic challenges in diverse indoor environments and industrial settings, where high-frequency noise-related problems are prevalent.

Materials and Methods

MPP acoustic impedance: The acoustic impedance of MPP was initially explored by Maa et al. [28]. MPP acoustic impedance comprises two components of real and imaginary parts. The real part of the impedance represents the viscosity loss experienced as the sound wave passes through the MPP holes, known as resistance. On the other hand, the imaginary part accounts for the moving air mass containing the sound wave between the holes referred to as reactance [20].
MPP acoustic impedance is calculated as follows:

Formula 1.

$$Z_{MPP} = Z_{Resistance} + Z_{Reactance} = r + j\omega m$$

Formula 2.

$$r = \frac{32\eta t}{\rho_0 c_0 d^2 p}\left[\sqrt{1+\frac{x^2}{32}}+\frac{xd\sqrt{2}}{32}+\frac{xd\sqrt{2}}{8t}\right]$$

Formula 3.

$$m = \frac{t}{pc_0}\left[1+(9+\frac{x^2}{2})^{-\frac{1}{2}}+\frac{85/0d}{t}\right]$$

Formula 4.

$$x = \frac{d}{2}\sqrt{\frac{\omega\rho}{\eta}}$$

In the given equations, the acoustic resistance and reactance, denoted by "r" and "m" respectively, are calculated based on various parameters. These parameters include the air density (ρ_0), the speed of sound waves in the air (c_0), the angular velocity (ω), the thickness of the MPP panel (t), the perforation percentage (p), the diameter of the holes (d), and the air viscosity (η) [20].

Acoustic impedance of fiber material placed below MPP: Allard and Champoux introduced a phenomenological mathematical model to examine the propagation of acoustic waves within fibrous porous materials [29]. Their study involved the utilization of two parameters, bulk modulus, and equivalent density, to calculate the acoustic impedance. Acoustic impedance is calculated as follows:

Formula 5.

$$\rho_w = \alpha_\infty \rho_0\left[1+\frac{\sigma\phi}{j\omega\alpha_\infty\rho_0}(1+\frac{4i\alpha_\infty{}^2\eta\omega\rho_0}{(\sigma\Lambda\phi)^2})^{\frac{1}{2}}\right]$$

Formula 6.

$$K_w = k\rho_0((k-(k-1)[1+\frac{8\eta\alpha_\infty\phi}{\acute{\Lambda}^2\phi i\omega\rho_0\alpha_\infty N_{pr}}(1+\frac{4i\alpha_\infty{}^2\eta N_{pr}\omega\rho_0}{(\sigma\acute{\Lambda}^2\phi)^2})^{\frac{1}{2}}$$

The equations involve several physical parameters, including σ (airflow resistivity), ϕ (porosity), α_∞ (tortuosity), Λ (viscous characteristic length), $\acute{\Lambda}$ (thermal characteristic length), ρ_0 (air density), N_{pr} (air Prandtl number, equal to 0.75), η (air viscosity, equal to 1.81×10^{-5} kg/m.s), k (air specific heat ratio, equal to 1.4), ω (angular velocity), $z_c(\omega)$ (characteristic impedance), and K_w (characteristic wave number). These parameters are essential for calculating the acoustic impedance within the fibrous porous materials, as proposed by Allard and Champoux [29].
The acoustic surface impedance of the porous absorber (Z_p) and the predicted acoustic absorption coefficient (K_c) can be calculated using the following equations:

Formula 7.

$$z_c(\omega) = \frac{1}{\emptyset}\sqrt{\rho_\omega.K_\omega}$$

Formula 8.

$$K_c(\omega) = \omega\sqrt{\frac{\rho(\omega)}{K(\omega)}}$$

Formula 9.

$$Z_p = z_c(\omega).\cot(K_c(\omega).d)$$

Finite Element Method (FEM): As previously mentioned, FEM was employed in this study to predict the total surface impedance (Z_s) and absorption coefficient. In FEM, a complex geometry is divided into smaller components with simpler geometries, and the relevant equations are solved for each of these components. When creating the FEM model, an impedance tube was constructed in accordance with the ISO10534-2 standard [30]. The 3D model of the impedance tube for the composite of porous material-MPP was designed with four distinct parts, arranged from top to bottom: the perfectly matched Layer, the background pressure field, the interior perforated plate, and the poroacoustics section. The perfectly matched Layer serves as the end part of the impedance tube where the sound source is positioned, creating an infinite air domain. Its primary function is to prevent any false sound reflections from occurring in the upper domain of the background pressure field [31]. The background pressure field in the designed model represents the incident sound wave generated by the source and propagating towards the absorbing material. This incident sound wave is considered a plane wave traveling in the z-axis direction. Within the FEM framework, the interior perforated plate is responsible for establishing the transfer impedance characteristics of the micro-perforated plate with round holes. To simulate the behavior of sound wave pressure as it interacts with and passes through the porous material, the poroacoustics section in the model utilizes the equivalent fluid model (EFM). This section accounts for the reduction and dispersion of sound wave pressure upon interaction with the porous material [31]. Regarding the poroacoustics section, there are several models available to calculate and predict the specific acoustic impedance of porous materials, among which the 5-parameter JCA model is commonly used. Compared to other experimental models such as DB, which rely solely on airflow resistivity for predicting sound absorption coefficient, the JCA model offers higher accuracy [32]. In the JCA model, in addition to airflow resistivity, parameters such as tortuosity, porosity, viscous characteristic length, and thermal characteristic length are utilized to calculate the acoustic impedance of the porous material. By inputting the relevant information and conducting the required steps, the COMSOL software calculates the frequency range, sound wave radiation angle, and normal absorption coefficient within the frequency range of 63 to 6300 Hz, using the FEM approach.

Acoustic parameters required in the JCA model.

Porosity ($\emptyset$): it is a critical parameter that significantly influences the acoustic performance of porous materials. It represents the volume fraction of air present within the material. The porosity value varies between 0 and 1, indicating the proportion of air volume compared to the total volume of the material [33].

Airflow resistivity (σ): it is the second significant parameter following porosity that impacts acoustic performance. It quantifies the air pressure difference between two sides of the sample relative to the average velocity of the airflow per unit thickness. A lower porosity increases higher airflow resistivity [34].

Tortuosity (α_∞): it is a dimensionless parameter which characterizes the influence of the material's internal structure on the airflow speed within the porous material. It solely depends on the internal shape and geometry of the material, representing the complexity of the airflow passage inside the material [35].

Viscous (Λ) and thermal ($\acute{\Lambda}$) characteristic lengths: they are utilized to describe the viscosity and thermal effects of the porous material at higher frequencies. They are solely related to the internal geometric structure of the material and are independent of the type of movement and airflow path inside the material [17].

Natural fibers: The simulation method was employed in this study, eliminating the need to create a physical sample. Therefore, the characteristics of areca nut natural fibers from Raj et al.'s research were utilized [27] which is shown in fig. 1. In Raj et al.'s study, they investigated the acoustic behavior of this material using the impedance tube experimental method, along with various predictive models such as DB, Miki, Allard, and Garai-Pompoli (GP), considering six different thicknesses. Due to its favorable absorption properties at low frequencies, unlike other natural fibers, areca nut natural fiber was deemed the most suitable choice for this study's primary objective, which aimed to enhance bandwidth and achieve high absorption at high frequencies when used in conjunction with MPP.

The Areca palm shown in fig. 1, widely cultivated in tropical regions of South Asia, is primarily valued for its fruit. The palm leaf sheath of the Areca nut is a significant component that keeps the connection between the trunk and branches strong. Once dried, these palm leaf sheaths serve as an excellent source of fibers with versatile applications, including the production of disposable catering plates [27].

The acoustic characteristics of Areca nut fibers used in the FEM are presented in Table 1.

Table 1. Acoustic characteristics of Areca nut fibers used from the study of Raj et al. (27)

Parameters	Value	Parameters	Value
Average thickness (mm)	6	**Bulk density ($\frac{Kg}{m^3}$)**	105
Average diameter (mm)	58.6	**Porosity ($\emptyset$)**	0.9189
Tortuosity (α_∞)	1.0441	**Air flow resistivity (σ) ($\frac{Rayl}{m}$)**	26789
Viscous characteristic length Λ (μm)	70.92	**Thermal characteristic length Λ´ (μm)**	141.84

Fig 1. Areca nut palm leaf sheath fibers used for simulation in this study [27].

Composite specifications modeled in COMSOL: In this research, the acoustic behavior of Areca nut fibers was explored using simulations with four different thicknesses (1 cm, 3 cm, 5 cm, and 7 cm) to determine the most optimal mode. Factors such as absorption coefficient, cost, and space limitations were considered to select the best thickness. Subsequently, the impact of the air layer behind the fiber material was investigated to understand its influence on the absorption coefficient and bandwidth. To further understand the overall behavior of the composite, the study examined the parameters of hole diameter, panel thickness, perforation, and various arrangements of fibers as well as MPP layering concerning the MPP absorber behavior.

Initially, the study focused on examining the effect of hole diameter. To achieve this, five different hole diameters (0.3 mm, 0.5 mm, 1 mm, 1.5 mm, and 2 mm) were designed, while keeping other parameters constant. The optimal mode, which aimed at increasing bandwidth and absorption at higher frequencies, was then selected based on the findings. Subsequently, the investigation turned to the impact of MPP panel thickness. Four different thicknesses (1 mm, 1.5 mm, 2 mm, 3 mm, and 4 mm) were considered, and the optimal mode for achieving the desired acoustic behavior was determined.

After determining the optimal hole diameter and panel thickness, the effect of perforation was examined at four different levels: 0.8%, 1%, 5%, and 10%. Subsequently, the study focused on the arrangement of fiber, MPP, and air layers to achieve the best acoustic performance. Three different arrangements were inspected:

1. In the first arrangement, the normal state, the order of layers was air layer, porous material layer, and MPP layer.
2. In the second arrangement, the order of layers was air layer, porous material, air layer, and porous material.
3. In the third arrangement, the order of layers was porous material, air layer, porous material, and air layer.

It is important to note that in all three arrangements, the order of layers is from bottom to top. Also, in the second and third arrangements, the thickness of each layer is half of that in the first arrangement. Fig. 2 demonstrates a visual representation of the various layer configurations.

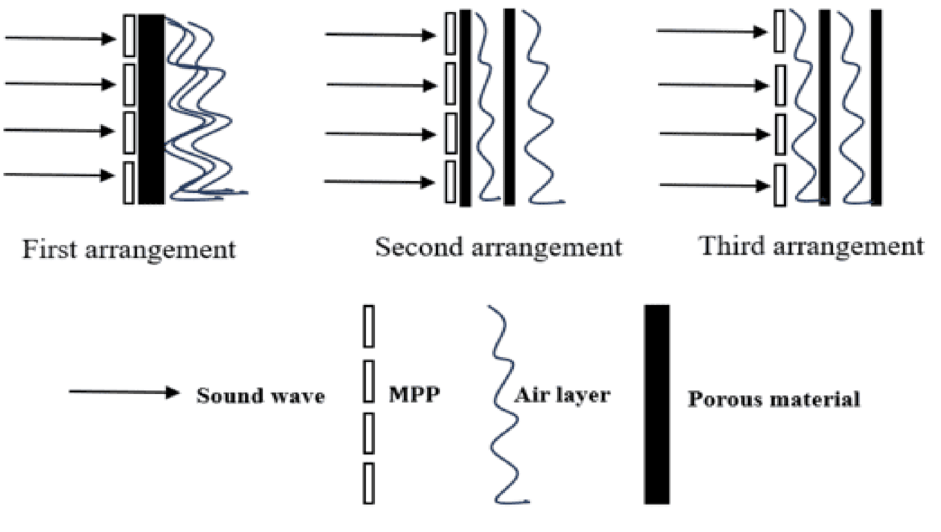

Fig. 2. The different layering of porous material, air layer, and MPP in order to investigate its effect on the acoustic behavior of the composite

Results

Acoustic behavior of fiber porous material without MPP in the frequency range of 63 to 6300 Hz: In this research, Areca nut fibers were employed in four different thicknesses of 1 cm, 3 cm, 5 cm, and 7 cm. The simulation of the absorption coefficient for these fiber thicknesses was conducted using FEM with the specifications provided in the reference study. Fig. 3 illustrates the results of these simulations.

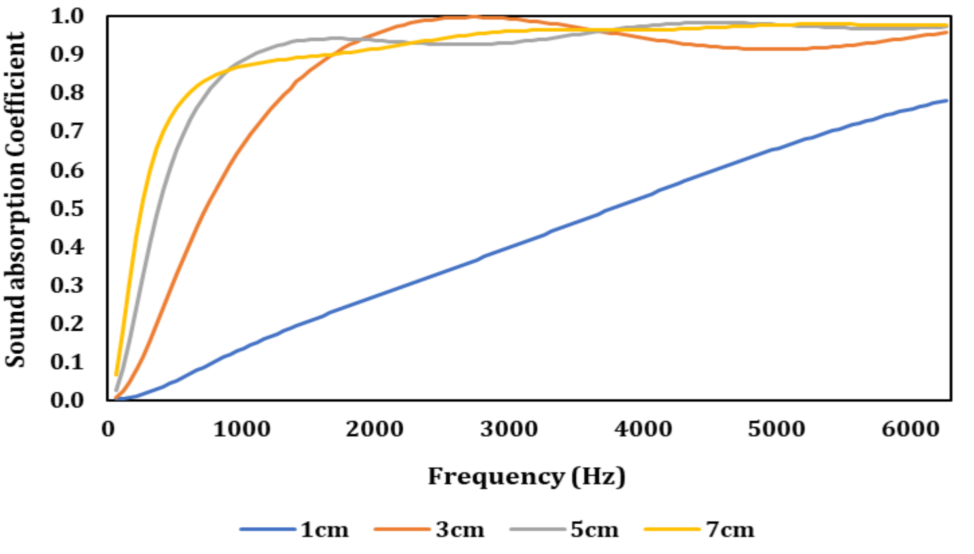

Fig. 3. Effect of porous material thickness on absorption coefficient and bandwidth

As depicted in Fig. 3, the absorption coefficient of the sample exhibits improvement across most frequencies as the thickness grows. The findings from increasing the thickness of the fiber layer demonstrate that both the absorption coefficient and bandwidth experience improvement. This enhancement is particularly noticeable at lower frequencies.

Acoustic behavior of fiber material with air layers in the frequency range of 63 to 6300 Hz (No MPP): In this study, before using the MPP, in order to explore the effect of adding an air layer behind the porous material and its effect on the absorption coefficient and bandwidth, three different thicknesses of 1, 2 and 3 cm air layer were used, with Fig. 4 showing the results of adding the air layer.

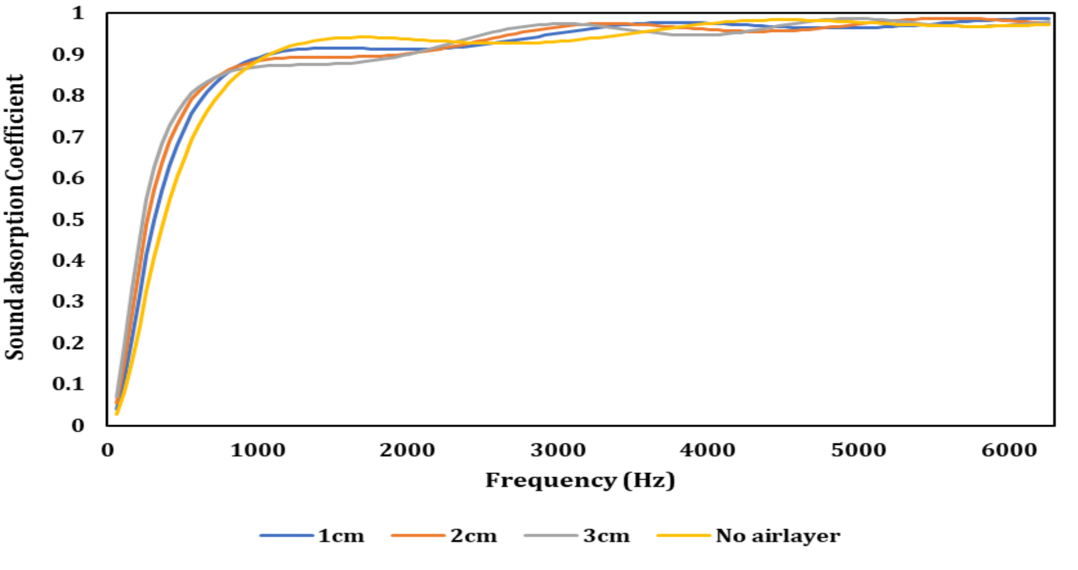

Fig. 4. The effect of adding air layers behind the porous material on the bandwidth and absorption coefficient

As displayed in Fig. 4, the introduction of an air layer and its subsequent increase in thickness behind the porous material has led to an improvement in both the absorption coefficient and bandwidth. For instance, by tripling the air layer thickness from 1 cm to 3 cm, one of the resonance peaks that initially occurred at 4200 Hz shifted to 3200 Hz in the 3 cm layer.

The effect of MPP hole diameter on the composite acoustic behavior: Following the selection of the optimal thickness for the fibrous material (5 cm) and the air layer behind it (3 cm), the subsequent step involved evaluating the impact of incorporating the MPP layer onto the porous material. The aim was to configure various MPP parameters to achieve appropriate absorption across low, middle, and high frequencies, thereby enhancing the overall bandwidth. Initially, the investigation focused solely on the effect of different MPP parameters, such as hole diameter, panel thickness, and perforation, without considering the presence of the air layer.

First of all, in our study we inspected the effect of hole diameter in various diameters on sound absorption, while assuming the panel thickness and perforation parameters to be constant. To explore the impact of hole diameter and identify the most optimal diameter to maintain composite good performance at high frequencies, five different diameters of 0.3, 0.5, 1, 1.5, and 2 mm were employed. Fig. 5 illustrates the acoustic behavior results of the composite with varying diameters while keeping other parameters constant.

As exhibited in Fig. 5, and as discussed in the introduction section, the addition of the MPP significantly impacts the composite's behavior at high frequencies, leading to a notable decline in absorption. However, at low frequencies, the absorption coefficient improved.

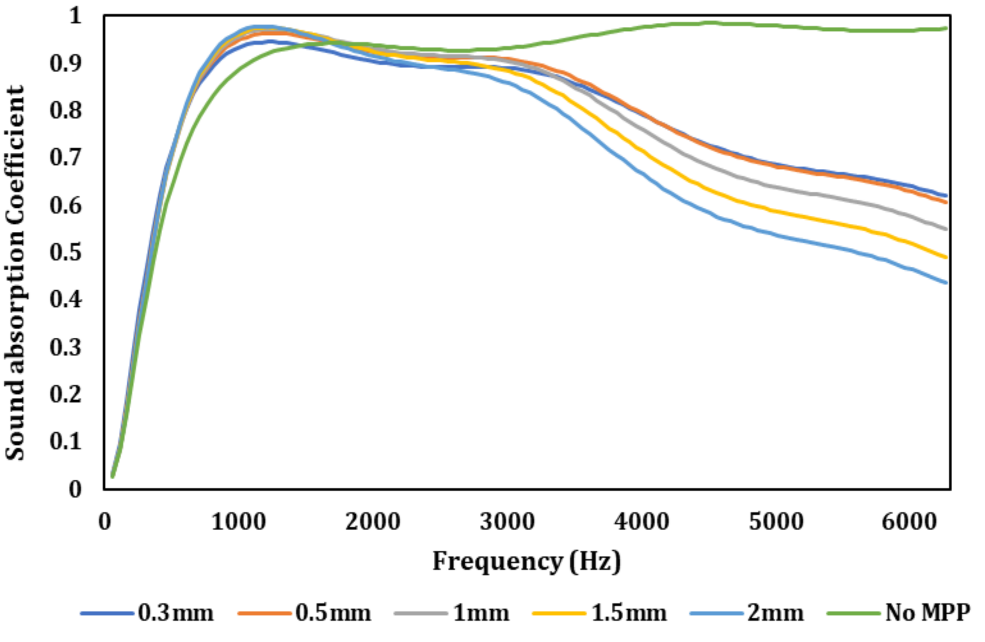

Fig. 5. The effect of the MPP hole diameters on the bandwidth and absorption coefficient of the composite

The effect of MPP panel thickness on composite acoustic behavior: After identifying the optimal hole diameter, the panel thickness was investigated by keeping the hole diameter and perforation percentage constant. Five different panel thicknesses (1 mm, 1.5 mm, 2 mm, 3 mm, and 4 mm) were investigated. The acoustic behavior of the composite in various panel thicknesses, while maintaining other parameters constant, is illustrated in Fig. 6.

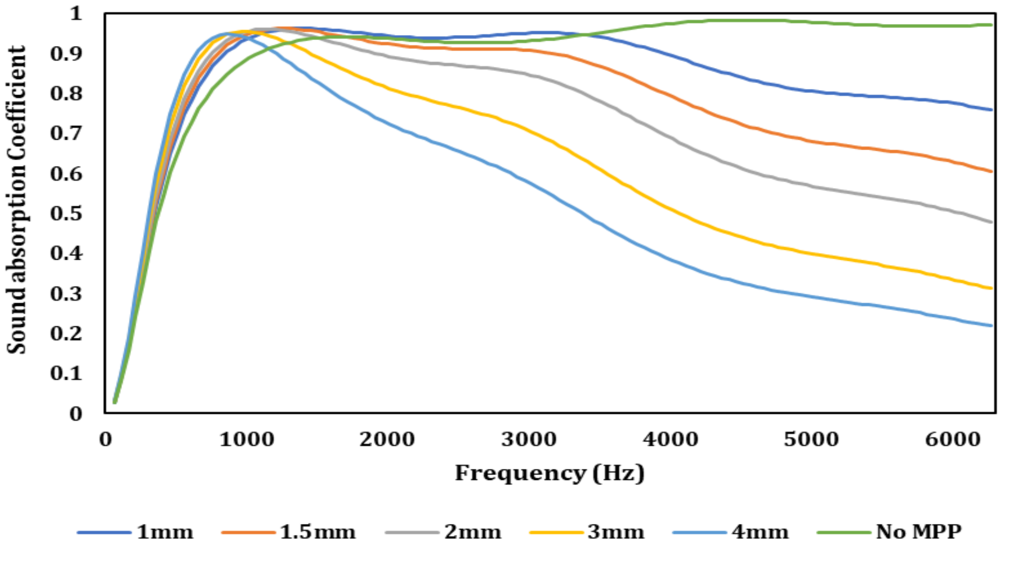

Fig. 6. The effect of MPP panel thickness on bandwidth and composite absorption coefficient

As depicted in Fig. 6, elevation of the thickness of the panel leads to an amplified resonance peak at low frequencies, accompanied by a reduction in bandwidth. Consequently, the composite's performance at high frequencies is significantly compromised. Conversely, reduction of the panel thickness results in a slight fall in absorption at low frequencies, leading to the disappearance of the resonance peak. However, this decline in thickness enhances the absorber's performance at high frequencies, making it comparable to the sample without MPP. Consequently, reducing the panel thickness yielded a broader bandwidth and improved sound absorption at high frequencies.

The effect of the MPP panel perforation on composite acoustic behavior: Perforation percentage refers to the ratio of the effective area of the holes to the total surface area of the panel. In this study, the effect of perforation percentage on the acoustic performance of the panel was examined. After identifying the optimal hole diameter (0.5mm) and panel thickness (1mm), four different perforation percentages (0.8%, 1%, 5%, and 10%) were investigated for the MPP panel. Fig. 7 indicates the results of the composite's acoustic behavior with varying percentages of perforation for the panel, while keeping other parameters constant.

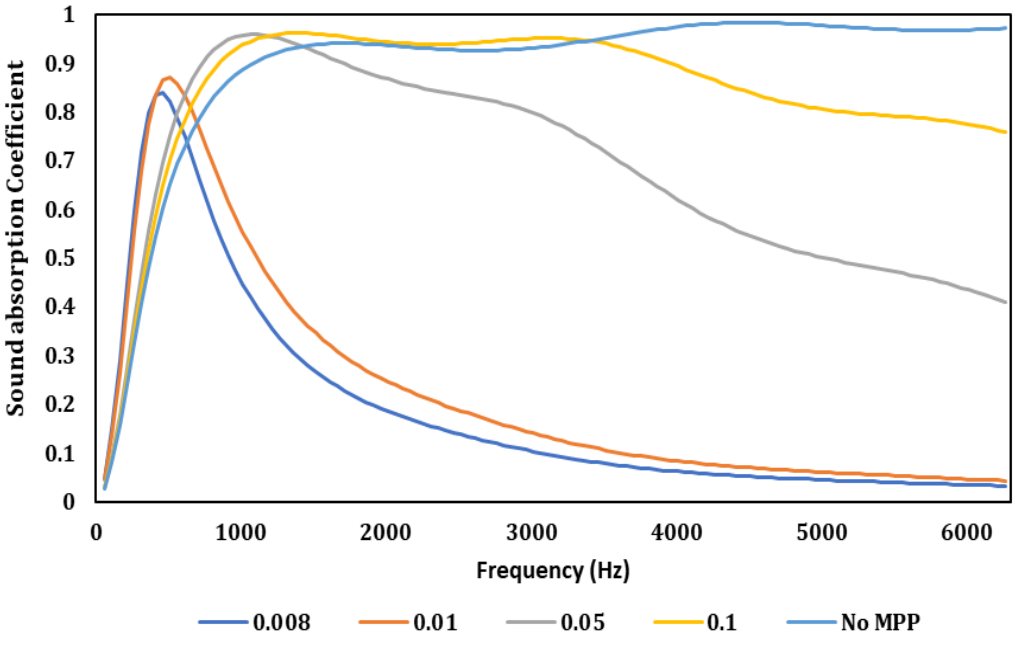

Fig. 7. The effect of MPP perforation percentage on the bandwidth and absorption coefficient of the composite

As illustrated in Figure 7, an increase in the perforation percentage resulted in improved absorption at high frequencies and an increase in the overall bandwidth. Conversely, a decline in perforation percentage led to enhanced absorption at low frequencies. Additionally, higher perforation percentages eliminated the resonance peak, leading to a broader bandwidth. Conversely, lower perforation resulted in stronger resonances and anti-resonances.

The effect of different layers of fibrous material and air layer behind the MPP on the acoustic behavior of the composite: In this section, the influence of various layering arrangements on the overall performance of the composite was examined through three distinct configurations. The objective was to determine whether the arrangement and different layering of the composite have any impact on its overall behavior and, if so, which mode is more suitable for enhancing the bandwidth towards higher frequencies. Hence, following the identification of the optimal settings for fiber thickness, air layer behind the fiber material, MPP hole diameter, MPP panel thickness, and MPP panel perforation percentage, various layering arrangements were examined. The general configuration of these layering arrangements is depicted in Fig. 2, while the outcomes of these configurations are presented in Fig. 8.

As evident, the combination of air layer, porous material, and MPP generally enhances absorption at low frequencies compared to the scenario without MPP. However, it results in reduced absorption at high frequencies. Among the three layering configurations, there are notable differences in bandwidth as well as absorption coefficients at high and low frequencies. Considering the present study's objectives of increasing bandwidth towards high frequencies, the optimal arrangement was configuration number two (air layer, porous material, air layer, porous material, and MPP).

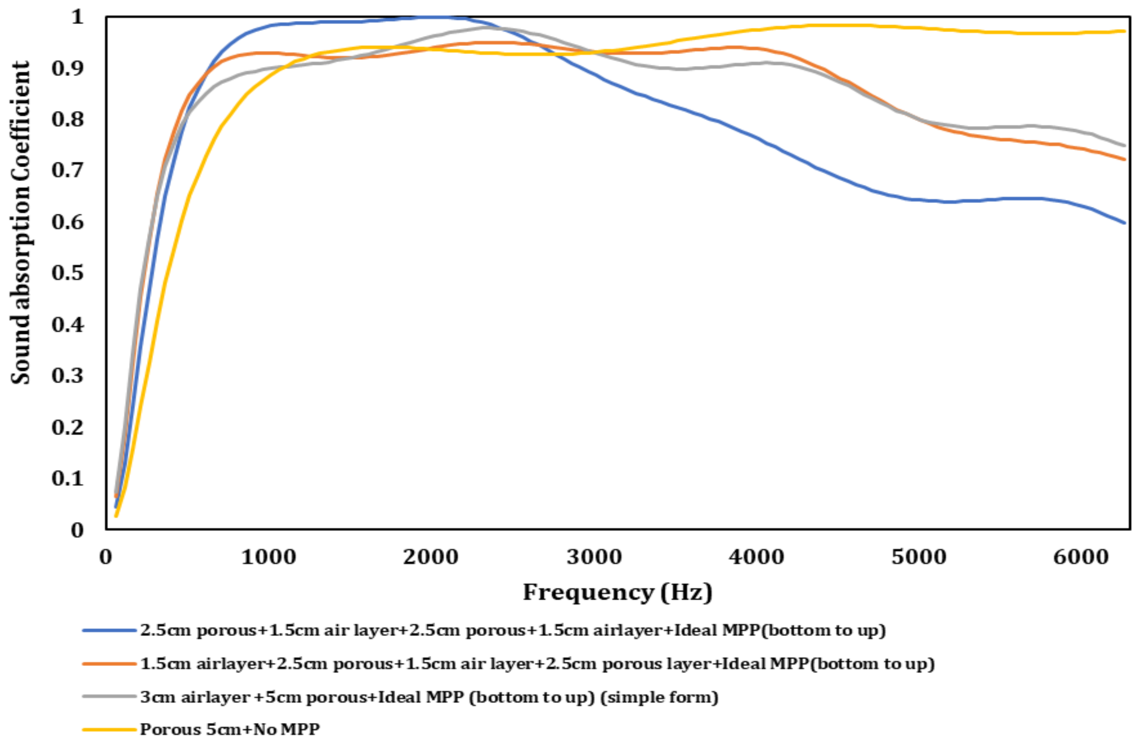

Fig. 8. The effect of different layers of porous material and the air layer behind the MPP on the bandwidth and absorption coefficient of the composite

Discussion

This study assessed the acoustic performance of a composite combining Areca nut natural fibers and MPP, examining various parameters such as fiber thickness, hole diameter, panel thickness, and MPP perforation on sound absorption coefficient using FEM. Three-layer configurations were analyzed to enhance low-frequency absorption while maintaining high-frequency performance. FEM simulations revealed that optimal selection of parameters can improve absorption across low, middle, and high frequencies as well as broaden the overall bandwidth. Factors such as fiber layer thickness, air layer placement, hole diameter, perforation percentage, panel thickness, and layer configuration contribute to expanding absorption bandwidth. These findings offer insights into effective noise control strategies.

Enlargement of the thickness of the fiber layer improved the absorption coefficient and bandwidth across most frequencies, with noticeable enhancement at lower frequencies, following the λ/4 rule where closer thickness to λ/4 (quarter wavelength) yields higher absorption [36]. Comparing the behaviors of the 5 cm and 7 cm thicknesses in this study reveals similar trends, with the 7 cm thickness exhibiting higher bandwidth at low frequencies. However, considering cost constraints and space limitations typically present in indoor environments, a thickness of 5 cm is deemed more optimal than 7 cm. The concept of increased absorption coefficient and bandwidth with thicker materials has been mentioned in numerous prior studies [11, 20, 27, 37]. Hence, to enhance the absorption coefficient of porous materials at various frequencies, magnification of their thickness is necessary. However, according to the λ/4, a massive thickness is required to achieve adequate absorption at low frequencies. For instance, at 200 Hz frequency, the ideal thickness for optimal absorption would be 177 cm, which is neither reasonable nor practical. Consequently, to effectively and reasonably expand the bandwidth at lower frequencies, incorporating an MPP layer atop the porous material is recommended.

The validation of the FEM results for the fibrous layer, in terms of the absorption coefficient at different thicknesses, was compared to the impedance tube measurements conducted in Raj et al.'s study. The comparison indicated that the FEM method with the JCA model accurately predicts the sound absorption coefficient and its accuracy is comparable to that of the direct impedance tube method. Deviations observed between the results from the present study and those obtained from the impedance tube in Raj's study may be attributed to real sample non-uniformity, manufacturing, and laboratory errors, which are not considered in the FEM simulations [20]. In Raj's study, various models, including JCA, were employed to predict the absorption coefficient of fiber samples with different thicknesses using the genetic algorithm and MATLAB software. The results were then compared to direct measurements using the impedance tube. Comparing the results from the FEM and JCA model in the present study with the genetic algorithm and the JCA model in Raj's study demonstrated that the FEM's accuracy is very similar to the genetic algorithm method. However, the advantage of using the FEM lies in its ease of implementation compared to the genetic algorithm method [27].

Use of an air layer is an effective method to elevate the absorption coefficient without increasing the thickness of the primary material, leading to cost savings. The results revealed that adding an air layer behind the porous material improves both absorption coefficient and bandwidth. While the air layer slightly improves the absorption coefficient at higher frequencies due to its limited thickness, its impact on enhancing absorption at low frequencies and widening the bandwidth is more significant. Enlargement of the air layer thickness enhances absorption at low frequencies, creating resonant peaks at lower frequencies. For example, tripling the air layer thickness from 1 cm to 3 cm shifts a resonance peak from 4200 Hz to 3200 Hz.

Increasing the air layer behind porous material raises impedance, shifting some resonant frequencies lower, thereby improving absorption at low frequencies [16]. However, in this study, increasing the air layer sometimes led to a decline in absorption coefficient at certain frequencies due to standing wave formation and destructive interference. Similar findings have been mentioned in relevant studies [15, 38].

Elevation of the diameter of MPP holes weakens composite behavior at high frequencies but improves it at lower frequencies, creating an absorption resonance peak that limits the absorption range. Conversely, reduction of the hole diameter widens the bandwidth by eliminating the resonance peak. The enhancement of the absorption coefficient with diminished hole diameter can be attributed to the increased real part of the impedance (acoustic resistance), viscosity loss, and airflow resistivity. As the hole diameter shrinks (within certain limits), it becomes more challenging for airflow to enter the holes, causing greater friction and converting a larger portion of the sound energy into heat [20]. The results of the present study have also been found in several other studies, including those conducted by Hashemi et al. [20], Beheshti et al. [11], and Rezaian et al. [19]. Consequently, based on the outcomes of various MPP hole diameters, it was observed that as the hole diameter falls, the absorber's performance improves at higher frequencies, leading to increased bandwidth. Nevertheless, it is crucial to consider the practicality and cost-effectiveness of manufacturing MPP with smaller hole diameters. Among the measured diameters, a diameter of 0.5 mm was selected as the optimal choice, as forming a 0.3 mm diameter presents some challenges. Conversely, enlargement of the diameter of the composite hole enhances the absorber's behavior at lower frequencies, but it reduces the overall bandwidth. Thus, if the objective is to design a resonance frequency covering a narrow range and create an absorber with more reactive behavior similar to Helmholtz absorbers, perforated panels with hole diameters larger than 1 mm would be more suitable compared to using MPP with sub-millimeter holes.

Increasing the thickness of the panel boosts resonance at low frequencies but reduces bandwidth, compromising performance at high frequencies. Conversely, reduction of thickness slightly lowers absorption at low frequencies, eliminating resonance peaks and improving high-frequency performance, leading to broader bandwidth. Improved acoustic performance with reduced thickness stems from enhanced acoustic matching between MPP and porous material, decreasing resonance, and improving layer interaction. Lower thickness lessens panel mass and stiffness, resulting in a smoother frequency response, diminishing resonance peaks, and widening bandwidth. To achieve high absorption at higher frequencies and broaden bandwidth, opting for lower panel thickness is advisable, but extreme thinness may compromise mechanical resistance. Use of high-quality materials such as aluminum can ensure structural integrity and manage construction costs effectively.

An increase in the perforation percentage resulted in improved absorption at high frequencies and an enhancement in the overall bandwidth. Conversely, a fall in perforation percentage led to enhanced absorption at low frequencies. Additionally, higher perforation percentages eliminated the resonance peak, leading to a broader bandwidth. Conversely, lower perforation resulted in stronger resonances and anti-resonances. Overall, the resonance peak is directly influenced by the perforation percentage, and as the percentage grows, the absorption coefficient peak shifts towards higher frequencies [20]. The primary reason behind the increase in the absorption coefficient and the decline in the resonance peak with an increment in the perforation lies in the reduction of acoustic resistance and reactance. This occurs because a higher number of holes (more perforation) allows more air mass to pass through the MPP and reach the underlying porous material. Additionally, as the number of holes increases, the mass and stiffness of the MPP decrease, leading to a reduction in structural resonances and acoustic reactance. Hence, the frequency response becomes smoother, resulting in a decline in the resonance peak. Furthermore, the increased percentage of holes facilitates airflow through the MPP, enhancing the acoustic matching between the MPP and the porous material. As such, a larger proportion of noise is converted into heat. These combined effects contribute to improved absorption at high frequencies and wider overall bandwidth. In line with the findings of our current investigation, Hashemi et al.'s research has demonstrated that an increase in perforation enhances absorption at higher frequencies [20]. Similarly, another study has indicated that reducing the percentage of perforation results in the absorption peak shifting towards lower frequencies, which aligns with the outcomes observed in our present study [39].

As evident, the combination of air layer, porous material, and MPP generally enhances absorption at low frequencies compared to the scenario without MPP. However, it results in reduced absorption at high frequencies. Among the three layering configurations, there are notable differences in bandwidth and absorption coefficients at high and low frequencies. Considering the present study's objectives of increasing bandwidth towards high frequencies, the optimal arrangement was configuration number two (air layer, porous material, air layer, porous material, and MPP).

Therefore, if the layering technique is to be employed, careful consideration of the layer arrangement becomes essential to achieve the desired outcome in noise control. The layering approach induces changes in absorption and bandwidth, particularly improving absorption at low frequencies. This improvement arises from the juxtaposition of materials with distinct surface impedance, creating various acoustic matches. Consequently, the noise weakens further as it passes through a differing surface impedance. The enhanced absorption at low frequencies is attributed to the inherent challenge of inhibiting low frequencies, owing to their long wavelengths. Strengthening the composite's resistance in terms of surface impedance is thus more effective in inhibiting lower frequencies. However, this increase in absorber resistance also results in a reduction in absorption at high frequencies, given that high frequencies possess shorter wavelengths and are more easily deflected [40].

Hence, it is evident that the determination of resonance frequency and bandwidth in the composite not only depends on the overall depth behind the MPP layer but also relies on the layering type and arrangement of these layers. The overall bandwidth of the absorber is significantly affected by the layering technique employed. By incorporating multiple layers and utilizing different materials with diverse acoustic parameters, such as tortuosity and airflow resistivity, the noise encounters more hindrances as it traverses through these layers. Thus, this impediment increases sound absorption within the composite [20].

The layering technique has been mentioned in various studies, exemplified by Hashemi's study where the use of layering resulted in lower resonance frequencies when the thickness of the porous material layer exceeded that of the air layer. This shift in resonance caused the absorption peak to move towards lower frequencies [20]. Similarly, Rusli et al. demonstrated that employing two MPP layers with different fiber materials in the layering technique led to increased bandwidth and higher absorption at lower frequencies [41]. Another study by Lim et al. revealed that incorporating a layer of hemp fibers with coconut fibers in the layering arrangement yielded better results and higher absorption coefficients, particularly when the hemp layer was positioned in the front part [42].

Another approach to enhance bandwidth in the layering technique involves using materials with higher bulk density. This increase in bulk density results in more fibers utilized per unit volume, causing the sound to encounter more resistance as it traverses through the material. Thus, higher proportion of sound energy is converted into heat [15].

The study challenges the common perception that a composite of porous materials and MPP primarily enhances low-frequency absorption, showing that careful parameter selection can broaden bandwidth and maintain high-frequency absorption. In industrial or office environments, high-frequency noise is problematic, making fibrous porous materials effective for noise control despite their challenges such as low mechanical resistance and limited low-frequency absorption. Combining porous fiber materials and MPP may reduce bandwidth, but careful parameter selection can lead to benefits including broad bandwidth, suitable absorption at both low and high frequencies, and enhanced resistance of the absorber. This enhancement includes mechanical strength, temperature, and humidity resistance, wind flow resilience, microbial attack resistance, and improved visual appearance. This suggests the potential for effective noise control with composite materials in various environments. Furthermore, the findings of this study indicated that employing FEM modeling can serve as a viable substitute for costly and intricate tools such as an impedance tube in predicting the acoustic characteristics of sound-absorbing materials.

For future investigations, it is recommended to explore the validation of the FEM by directly measuring the sound absorption coefficient with an impedance tube. This would enable a better understanding of the application of the FEM. Additionally, comparing the results obtained from FEM simulations with other natural fibers against experimental results from the impedance tube would be valuable in assessing the accuracy and reliability of the FEM approach.

Conclusion

This study demonstrated that careful selection and optimization of dimensional and macroscopic parameters of the MPP porous material layer and absorber can enhance the overall effectiveness of the composite. By optimizing these parameters, the composite showed good bandwidth and presented improved absorption performance at low, middle, and high frequencies, along with enhanced resistance to environmental factors. Factors such as fiber layer thickness, air layer presence, hole diameter, perforation percentage, and panel thickness play crucial roles in enhancing the composite's absorption bandwidth. For higher absorption at high frequencies and broader bandwidth, smaller diameter holes and thinner panels with higher perforation percentages are recommended. Conversely, for increased absorption at low frequencies or specific frequency ranges, larger hole diameters and thicker panels with reduced perforation are more suitable. The integration of fiber material and MPP not only mitigates the dispersion of fiber particles in various settings such as offices, restaurants, and hospitals, thus averting potential skin and respiratory issues for individuals but also bolsters the mechanical resilience of fiber absorbers in demanding industrial environments. Numerical simulation methods such as FEM offer cost-effective and accurate alternatives to experimental methods, making them valuable tools for studying acoustic behavior and optimizing composite materials for noise control applications.

Acknowledgement

We are thankful to everyone providing the necessary facilities for this work.

Conflict of interest

None declared.

Funding

The journal is informed that we did not have any funding for this article.

Ethical Considerations

This Study does not include any particular ethical concerns.

Code of Ethics

This study was approved by the Ethics Committee of Tehran University of Medical Sciences (Ethics code: IR.TUMS.SPH.REC.1401.088).

Authors' Contributions

Mohammad Javad SheikhMozafari: the study conception and design, Data collection and analysis, the first draft of the manuscript was written, the final Manuscript was read and approved.
Akbar Ahmadi Asour: the study conception and design, the first draft of the manuscript was written, the final Manuscript was read and approved.
Sara Hajinejad: the study conception and design, the first draft of the manuscript was written, the final Manuscript was read and approved.

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