Original Article

Determining the Sound Absorption Coefficient of Bamboo Composites: Theoretical- and Laboratory-based Approaches

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Abstract

Aim: The use of natural fiber-based composites in various applications is increasing due to their cost-effectiveness, low density, nontoxicity, and environmental friendliness. Therefore, in this study, the acoustic performance of natural bamboo fiber composites was investigated using experimental and theoretical methods. The properties of these composites, which include affordability, low density, nontoxicity, and eco-friendliness, contribute to their growing popularity. **Methods:** In this study, three types of composites with a density of 200 kg/m^3 and thicknesses of 50 mm were fabricated. The normal incidence absorption coefficient was directly measured using the impedance tube method based on the ISO 10534-2 standard. In addition, for predicting the sound absorption coefficient of the composites, the software COMSOL and the Miki and Attenborough models were utilized. **Results:** The results indicate that for samples F (fine fiber) and F-C (fine coarse fiber), the average sound absorption above 1000 Hz is 0.8. The sound absorption values in sample C (coarse fiber) were lower than those in samples F and F-C. In addition, the mathematical models of Miki and Attenborough can predict the acoustic behavior of the samples to some extent, with the Attenborough model providing higher accuracy in its predictions. **Conclusion:** The results of this study demonstrate that a composite composed of natural bamboo fibers can be used as a sound-absorbing material for noise control purposes, while also contributing as a green technology replacing natural fibers with synthetic fibers.

Keywords: Bamboo fiber, experimental and theoretical comparison, sound absorption coefficient

INTRODUCTION

In the development of urbanization and transportation, noise pollution was disregarded as a disturbing yet harmless factor. However, nowadays, the general public has become aware that noise not only significantly affects work quality and living standards but can also lead to a range of health issues, including hearing loss, sleep disorders, fatigue, cardiovascular problems, and psychophysiological disturbances.[1,2] According to the statistics of the World Health Organization, over 1.6 million healthy years of life are lost annually in Western Europe due to traffic-related noise, and the impact of noise pollution on health and the environment ranks second after air pollution.[3]

Currently, there is an increasing trend in designing products with reduced daily noise production. However, aside from the design, it often becomes necessary to utilize techniques that decrease the noise level in the product or industrial application. Commercial sound-absorbing materials can generally be divided into two categories: resonant absorbers (intensifiers) and porous absorbers. Resonant absorbers mainly include Helmholtz resonators, perforated panels, and membrane absorbers. These sound absorbers rely on the principle of internal resonance, providing them with good absorption properties at low frequencies. One of the main drawbacks of this type of sound absorbers is their narrow frequency band range.[4] Sound-absorbing porous materials are formed by channels, cracks, or cavities that allow sound waves to enter these materials. The input sound energy is dissipated within the porous materials due

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to heat loss caused by friction between air molecules and the walls of the channels, as well as viscous dissipation by the flow of viscous air within the materials. These energy dissipation principles enable porous materials to absorb sound across a wide frequency range.[5,6] Sound-absorbing composite materials available in the market can be divided into three types: fibrous, granular, and cellular. Fibrous sound-absorbing materials are categorized into two groups, natural and synthetic, based on the origin of the fibers. The use of composite materials based on natural fibers is rapidly increasing due to their environmental compatibility, high wear resistance, low emission of toxic vapors when exposed to heat, high specific strength, lightweight, renewability, and cost-effectiveness.[7,8] Due to their extensive applications in automotive, sports, aerospace, and civil engineering, such composite materials receive a great deal of attention. Fiber-based composites are a combination of fibers and a matrix, resulting in materials with improved mechanical properties compared to fibers and matrices separately.[9,10]

Bamboo, as one of the sources of natural fiber production, has over 1250 species worldwide, with a global production reaching 10 × 106 tons, making it the third-largest source of wood and cellulose products after wood and cotton.[8] The superior strength and lightweight nature of bamboo, along with its resistance to fungi and insect attacks, suggest it is a potential alternative raw material for producing biocomposite products.[11,12] In the study conducted by Mamtaz *et al*., it was found that using nonuniform filler fibers can enhance sound absorption at low- and mid-range frequencies.[13] As mentioned earlier, one of the main challenges of natural fibers is their susceptibility to attacks by fungi and bacteria. Raru *et al*. conducted a comprehensive review of the antibacterial properties of bamboo, revealing that bamboo fibers possess strong antibacterial properties that persist even after 50 industrial washes.[14] Taban *et al*., on the other hand, employed a biodegradable binder known as polyvinyl alcohol (PVA) to develop a sound composite based on natural fibers. The results demonstrated a favorable interaction between the natural fibers and PVA, resulting in satisfactory composite properties and acceptable performance.[15]

Various methods can be used to directly measure the sound absorption coefficient, including the reverberation room method and the impedance tube method. Among these methods, the impedance tube method is the most accurate and commonly used. According to ISO standards, there are two methods for measuring the absorption coefficient using the impedance tube: the standing wave method (ISO 10534-1.1996) and the transfer function method (ISO 10534-2.1998). It is worth mentioning that the transfer function method allows for faster measurements.[3,16] In addition, it should be mentioned that the impedance tube method only provides the sound absorption coefficient under normal incidence conditions.[16] In addition to direct measurement methods of the sound absorption coefficient, many researchers have proposed mathematical relationships and formulas as predictive models for determining the best fit between experimental and theoretical values.[16,17] Theoretical models are classified into empirical and phenomenological models.[18] Empirical models are also known as single-parameter models, as they consider the material porosity, and the characteristic impedance and propagation constant depend solely on the airflow resistivity (AFR) quantity. With the AFR value, these models can predict the sound absorption coefficient of materials. The Miki model is one of the empirical models, which is an improved version of the Delany–Bazley model and exhibits better prediction capabilities, especially in the frequency range of $f < 400$ Hz.[19,20] Phenomenological models, or multi-parameter models, determine the characteristic impedance and propagation constant of a porous material based on parameters such as tortuosity, porosity, and AFR with a microscopic perspective. The Attenborough model is also one of the phenomenological models.[19,20] Working with phenomenological models and acoustical modeling of porous materials requires parameters such as AFR, porosity, tortuosity, viscous characteristic length, and thermal characteristic length, which are challenging to directly measure, especially the latter three. Therefore, inverse methods are used to determine these parameters. The commercial software FOAM-X, developed by ESI, is one of the software tools that perform the inverse method's complex mathematical equations to accurately and reliably determine the nonacoustic parameters from impedance tube measurements.[21]

This study aimed to determine the sound absorption coefficient of bamboo composite using two methods, theoretical (mathematical models) and experimental, and to compare. In this study, the software COMSOL V5.6 was used for numerical calculations and theoretical determination of the sound absorption coefficient of the bamboo composite, employing the Miki and Attenborough models. To validate the results, these findings were compared with experimental measurements extracted from impedance tube measurements.

MATERIALS AND METHODS

Materials

In this study, sodium hydroxide (NaOH >95%) was branded as Dr. Mojalli (Iran), and PVA adhesive of extra pure grade branded as Neutron (Iran) was used. To prepare the PVA adhesive, a certain amount of PVA powder was weighed according to the desired adhesive concentration and mixed with a specific volume of distilled water for 4 h at 80°C.

Preparation of bamboo fibers

Bamboo stems used in this study, with a diameter of 30–50 mm, were obtained from the town of Fouman (a town in northern Iran). In the next step, bamboo fibers were extracted using two methods. In the first method, for the extraction of fine bamboo fibers, the internodal sections of the bamboo stem were separated and cut into strips with a thickness of 0.5–1 mm and a width of approximately 10 mm. These bamboo strips were then immersed in a 5% w/v NaOH solution for 48 h. Afterward, the alkaline strips were rinsed multiple times with water, and the fibers were extracted using a sharp knife and a process of combing and scraping. After another rinse with water, the fibers were air-dried. Finally, the obtained fibers were cut into a size of 10–20 mm.

In the second method, for the preparation of coarse bamboo fibers, dry bamboo stems were shredded using a Drum Chipper machine. Then, the smaller pieces were further cut using a Ring Flaker machine. Subsequently, to improve the surface properties and increase roughness, the bamboo pieces were immersed in a 4% w/v NaOH solution for 6 h and then thoroughly rinsed with water.[12,22,23]

Sample preparation

In this stage, based on previous studies, the structural parameters of the bamboo composite were determined according to the conditions specified in Table 1. To fabricate the samples, a specific mass of bamboo fibers was weighed. Then, considering the total mass of the filler with a constant ratio (ratio between filler mass and adhesive volume), the PVA adhesive was mixed. The samples were then molded using steel molds with 30 and 100 mm (corresponding to the impedance tube diameters). Subsequently, the samples were air-dried for 1 week, and weight changes were noted to ensure complete drying of the samples.[16]

Measurement

Sound absorption measurement

In this study, measurements of sound absorption under normal incidence were performed using a two-microphone impedance tube (BSWA Technology Co., Ltd) and the ISO10534-2 method. Device calibration was conducted with a sound level of 114 decibels at a frequency of 1000 Hz before the experiments were carried out, ensuring accuracy and verification. All tests were conducted in controlled environmental conditions within an anechoic room. To eliminate operator and equipment errors, each sample measurement was repeated three times, and the results were reported as the average.

For presenting the sound absorption results of the samples, the sound absorption average (SAA) was determined using the ASTM C423 standard.[24] The following procedure was followed to determine the SAA index:

$$SAA = \frac{1}{12}\sum_{i=200\,Hz}^{i=2500Hz} \alpha_i \tag{1}$$

Where αi represents the sound absorption coefficient (SAC) for 12 frequencies (200–2500 Hz) in one-third of octave bands.

Measurement of physical properties

Thickness

Following the ASTM D1037 standard, we created cylindrical samples with specific thicknesses under steady temperature and pressure conditions. The thickness of each sample was determined by taking three measurements using a digital thickness gauge.

Bulk density

We determined the bulk density of the samples by dividing mass by their volume.

Porosity determination

This ratio shows the volume of interconnected pores connected to the external surface of a porous medium to its total volume. It is one of the vital parameters affecting the acoustic properties of porous materials. The porosity can be obtained from the following equation:

$$\varphi = 1 - \frac{\rho_{bulk}}{\rho_{fiber}} \tag{2}$$

In the above equation, ρ_bulk indicates the apparent density of the environment, and ρ_fiber suggests the density of the fibers, which for fine and coarse fibers, the respective were 666 and 714 kg/m^3.

Airflow resistivity

AFR was calculated according to ISO 9053 standards and using equation 3, where the factors P1 and P2 represent the pressure at the front and back of the sample, respectively. Factors *A* and *d* represented the cross-sectional area and thickness of the sample, while *Q* symbolized the flow of the passing fluid. The pressure drop at a given flow rate was measured using a digital differential pressure gauge, Testo 512 (Testo Co., Lenzkirch, Germany).

$$\sigma = A\frac{(P_2 - P_1)}{Qd} \tag{3}$$

Torosity determination

At this stage, using the software Foam-X and the inverse method, the value of tortuosity was determined for the samples based on the absorption coefficient curves, porosity parameters, AFR, thickness, and density of the composites.

Morphological analysis using field emission scanning electron microscope

Field emission scanning electron microscope (FESEM), TESCAN MIRA3 model, was used for morphological analysis of samples and determination of fiber diameter.

Table 1: Composite structural parameters

Sample ID	Fiber type	Density (kg/m^3)	Binder concentration (%w/v)	Thickness (mm)
F	Fine fiber	200	15	50
C	Coarse fiber			
F-C	Fine and coarse fiber (with equal ratio)			

Sound absorption prediction

After determining the physical parameters of the composites, the impedance tube is first modeled along with the sample in the COMSOL software to model sound propagation and calculate the sound absorption coefficient. After defining the boundary and initial conditions and setting up the physics of the problem in the "Pro Acoustic" section, the Miki and Attenborough models are selected. The specified physical parameters for the samples are then entered in this section, and finally, the sound absorption coefficient of the sample is calculated.[15,25,26]

Miki model

The Miki model is an empirical model that is an improved version of the Delany–Bazley model. It proposes a simple model for predicting the acoustic properties of fibrous absorbent materials using a nonacoustic parameter called AFR. In this method, by knowing the AFR of the sample (σ) and using equations 4 and 5, the characteristic wave impedance (z_c) and characteristic wave number (k_c) can be determined. Subsequently, the normal incidence sound absorption coefficient can be determined.[19]

$$Z_c = \rho_0 C_0 \left[1 + 0.070 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.632} - i0.107 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.632} \right] \quad (4)$$

$$K_c = \frac{\omega}{C_0} \left[1 + 0.160 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.618} - i0.109 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.618} \right] \quad (5)$$

In the above equations, $\rho_0 C_0$ represents the characteristic impedance (Pa s/m), $\omega = 2\pi f$ is the angular frequency, C is the speed of sound (m/s), σ is the AFR (Rayl/m), and f is the frequency (Hz). By having the two parameters Zs and R, the normal incidence sound absorption coefficient α can be calculated using equations 6–8, where Zs is the surface impedance and *R* is the sound reflection coefficient.

$$Z_s = -jZ_c cot(K_c d) \quad (6)$$

$$R = \frac{Z_s - \rho_0 C_0}{Z_s + \rho_0 C_0} \quad (7)$$

$$\alpha = 1 - |R|^2 \quad (8)$$

Attenborough model

The Attenborough model is a semi-empirical four-parameter model based on the assumption of rigid-walled cylindrical pores. This model is an extension of the Zwikker–Kosten model and incorporates two additional parameters: tortuosity and hydraulic diameter. Tortuosity represents the deviation of sound propagation direction relative to the absorbent pores, mainly applicable at higher frequencies. The hydraulic diameter of the pores is replaced by an alternative expression involving the equivalent circular radius (AFR) and a fitting parameter (b), which accounts for pore nonuniformity.[27] The equivalent density $\tilde{\rho}(\omega)$ and bulk modulus $\tilde{K}(\omega)$ are defined as follows:

$$\tilde{\rho}(\omega) = \alpha_\infty \rho_0 \left(1 - \frac{2}{\lambda\sqrt{-i}} T(\zeta)\left(\lambda\sqrt{-i}\right)\right)^{-1} \quad (9)$$

$$T = \frac{J_1(\zeta)}{J_0(\zeta)} \quad (10)$$

Where tortuosity α_∞, air density ρ_0, and T is the ratio of Bessel functions of the first and zero orders. The value of λ for noncircular cross-section pores is calculated using equation 11.

$$\lambda = \frac{1}{2S_A} \sqrt{\frac{8\alpha_\infty \rho_0 \omega}{\sigma_f \varnothing}} \quad (11)$$

The AFR inside the sample is denoted as σ_f, the porosity of the sample is represented by ∅, the tortuosity is α_∞, and the structure factor S_A is dependent on the geometric shape of the porous material.

$$\tilde{K}(\omega) = KP_0\left(1 - \frac{2(K-1)}{N_{pr}^{1/2}\lambda\sqrt{-i}} T\left(N_{pr}^{1/2}\lambda\sqrt{-i}\right)\right)^{-1} \quad (12)$$

The Prandtl number for air is denoted as N_{pr}, and K is the specific heat ratio for air. Then, using the following equations, the characteristic impedance $Z_c(\omega)$ and characteristic wave number $K_c(\omega)$ can be calculated, as well as the surface acoustic impedance Z_s. Finally, using equations 7 and 8, the value of the sound absorption coefficient can be computed.

$$Z_c(\omega) = \frac{1}{\varnothing}\sqrt{\rho(w).K(\omega)} \quad (13)$$

$$K_c(\omega) = \omega\sqrt{\frac{\rho(\omega)}{K(\omega)}} \quad (14)$$

$$Z_s = Z_C(\omega).coth(k_c(\omega)) \quad (15)$$

RESULTS

The morphology and diameter of the fibers were inspected using the FESEM images. These images were magnified from 30 to 35,000 times for analysis. As shown in Figure 1, the bamboo fibers have a circular cross-section. To determine the diameter of the prepared fibers, several fields from FESEM images were selected using Digimizer software, and the diameter of 10 randomly chosen fibers was measured. Then, the average fiber diameter was calculated, resulting in average diameters of 11.8 and 56.9 μm for fine and coarse fibers, respectively. In addition, after volumetric measurements of different bamboo samples to determine their mass, the density of bamboo fibers for fine and coarse fibers was calculated as 666 and 714 kg/m^3, respectively.

The physical parameters of the samples, which have been calculated using direct and inverse methods, are presented in Table 2. These parameters were used to determine the sound absorption coefficient of the composites using the theoretical method.

Figure 2 illustrates the results of the sound absorption coefficient of bamboo biocomposites, determined using

Table 2: Physical properties of samples

Sample	Thickness (mm)	Density (kg/m^3)	Airflow resistivity (N/m4.s)	Porosity (φ)	Tortuosity (α_∞)
F	50	200	6490	0.69	1.76
C	50	200	6210	0.72	1.54
F-C	50	200	6305	0.7	1.62

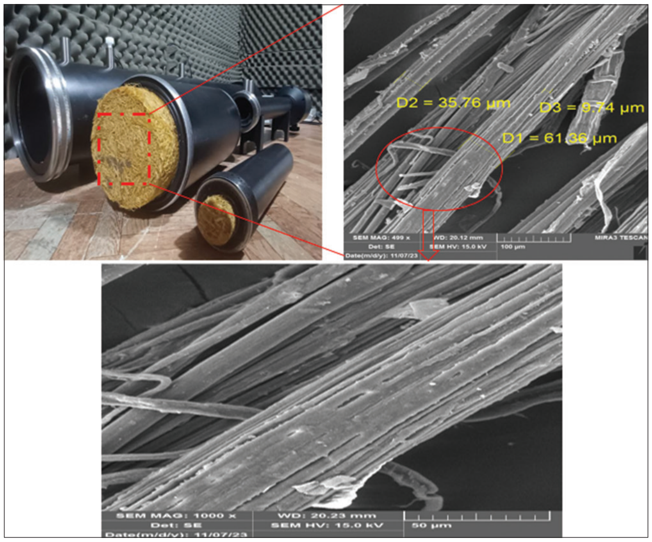

Figure 1: Field emission scanning electron microscope (FESEM) image of bamboo fiber at the different magnifications

laboratory experimentation and the impedance tube method. As observed, samples F and F-C exhibit consistent competition in terms of sound absorption coefficient and demonstrate higher values compared to sample C. The values of SAA were calculated as 0.525, 0.520, and 0.446 for samples F, F-C, and C, respectively.

In Figure 3, the results of the sound absorption of bamboo composite samples are presented, both through laboratory experimentation and using two theoretical models, Miki and Attenborough. As observed, in all three samples, the Attenborough model, which is a phenomenological model, shows better agreement with the experimental results. In all three samples, the Miki model demonstrates good agreement with the experimental results at frequencies below 1000 Hz. However, at higher frequencies, the model predicts higher values for the sound absorption of the composites, leading to increased errors in accurately predicting the sound absorption of the composites.

DISCUSSION

In this study, SAC graphs were used to investigate the acoustic properties of composites made from bamboo fibers. As the results showed, the SAC level of sample C was lower than the other two samples at all frequencies, and the F-C sample performed better than the F sample at frequencies below 4000 and 200 Hz. The F sample, however, had better SAC performance at other frequencies. Samaei *et al*. reported that increasing the fiber-to-granule ratio led to improved sound absorption behavior of fiber-granule composites and a shift of the SAC peak toward lower frequency bands. They attributed this to changes in electrical resistivity resulting from variations in fiber radius.[28]

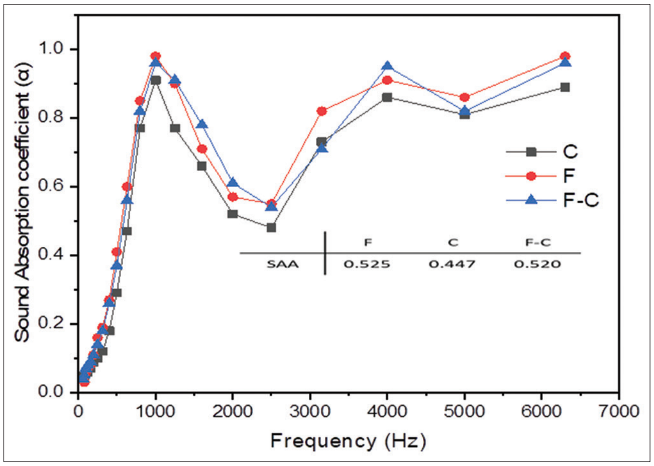

Figure 2: Sound absorption coefficient at the different filler composite

The study by Mamtaz *et al*., focusing on the acoustic absorbers of fiber-granule composites, showed that a combination of fibers and granules can lead to the improvement of acoustic properties in composites as stable and reliable sound absorbers, particularly at low frequencies. They also mentioned that a composite with thinner fibers and smaller granules would have a higher surface area, a more tortuous path, and higher airflow resistance. As a result, this would lead to a higher absorption coefficient and a shift of the peak toward lower frequencies.[13]

The results indicated that the bamboo fiber absorber (for samples C and F-C) exhibited good sound absorption coefficients, especially at frequencies above 1000 Hz, with an average sound absorption of 0.8 in the range above 1000 Hz. This value could be further improved by increasing the density to some extent. Or *et al*. reported that oil palm fiber samples with a thickness of 40 and 50 mm and a density of 292 kg/m^3 have an average sound absorption of 0.9 at frequencies above 1 kHz. It was also mentioned that by creating an optimal density, good sound absorption can be achieved for fibers, and the absorber's performance can be improved at lower frequencies by creating air gap cavities behind the panel.[29]

In this study, we used the direct laboratory experimental method, as well as the empirical model of Miki and the phenomenological model of Attenborough, to predict the

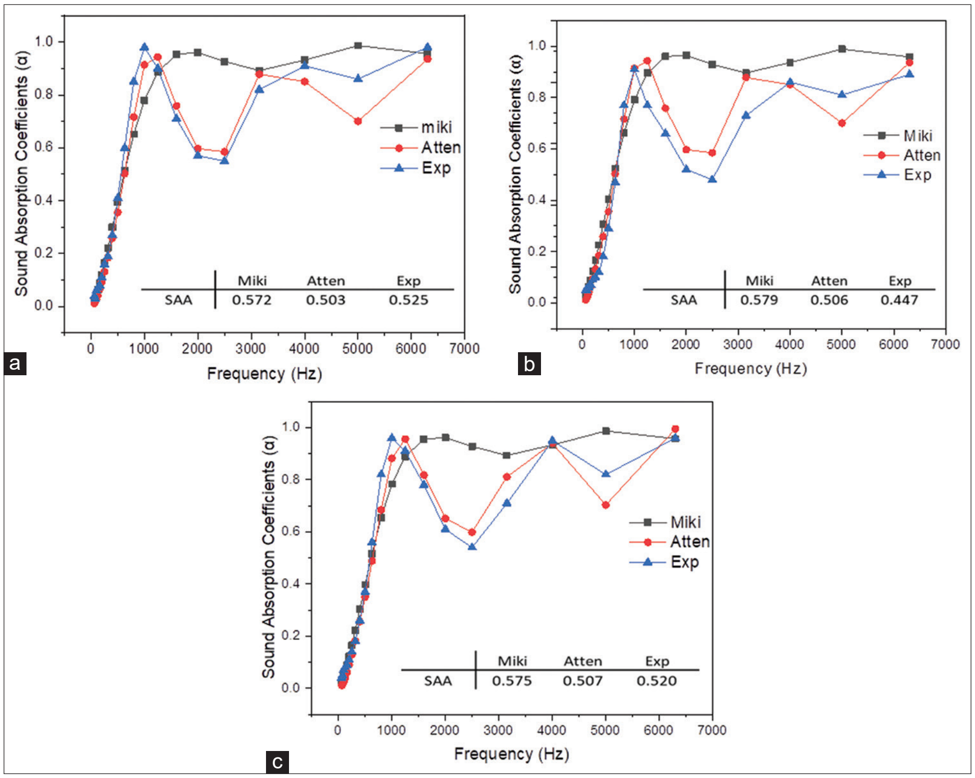

Figure 3: Comparison of the experimental sound absorption coefficients with the Attenborough and Miki models (a) F sample, (b) C sample, and (c) F-C sample.

sound absorption coefficients of the samples. As observed in the presented results in Figure 3, the Miki model does not agree with the experimental data, especially at frequencies above 1000 Hz, while the Attenborough model can capture the trend of the experimental data and their values in the broader frequency range with an acceptable error. It is observed that both the Attenborough and Miki models exhibit almost the same level of accuracy when it comes to frequencies below 1000 Hz. The obtained values of SAA, both experimentally and predicted by the Attenborough and Miki models, for Sample F, were 0.525, 0.503, and 0.572, for Sample C were 0.447, 0.506, and 0.579, and for F-C were 0.520, 0.507, and 0.575, respectively. As observed, the Attenborough model predicted the SAA values with a lower error than the Miki model in all three samples. Kalauni and Pawar also mentioned that empirical models are simple and accessible models for quickly approximating the sound absorption coefficient of porous materials using only the airflow resistance. On the other hand, phenomenological models are superior to empirical models, but they are more complex and challenging as they use additional parameters to predict the sound absorption coefficient.[30]

CONCLUSION

The results of this study demonstrated that a composite composed of natural bamboo fibers can used as a sound-absorbing material for sound control purposes. The sound absorption of the composite was examined using the Miki and Attenborough models in the COMSOL software environment, and experimental investigations were conducted to validate the theoretical approach using impedance tubes. The theoretical and experimental data indicated that at frequencies above 1000 Hz, the sound absorption coefficient of the composite was within the range of 0.8. If necessary, the absorption level at frequencies below 1000 Hz could be improved by introducing an air cavity behind the panel. Ultimately, the current research contributes to green technology by promoting the substitution of natural fibers with synthetic fibers, and it facilitates the use of natural fibers as sound-absorbing materials with low manufacturing costs. However, one of the limitations of the current study is the lack of control over fiber diameter (fine and coarse) and their composition ratios at different diameters. Therefore, it seems that to achieve higher efficiencies, especially in low and mid-range frequencies, investigating the mentioned aspects could be beneficial.

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Ethics code

IR.MODARES.REC.1402.105.

Conflicts of interest

There are no conflicts of interest.

Authors' contributions

Hassan Irvani: Conceptualization, Methodology, Software, Analysis, and validation of data, Writing, Hassan Asilian Mahabadi: Conceptualization, Methodology, Writing, review, and editing, Ali Khavanin: Conceptualization, Methodology, Writing, review, and editing, Ali Safari Variani: Conceptualization, Methodology, Writing, review, and editing.

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