Sustainable Acoustic Absorbers: Fabrication and Sound Absorption Performance of Compression-Molded Composites Derived from Bamboo Leaf Waste

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Abstract

This research addresses the issue by developing a novel, eco-friendly acoustic absorbing material that aligns with the principles of the Bio-Circular-Green (BCG) Economy. The study utilizes dry bamboo leaf powder as the primary natural fiber and Persea kurzii powder, a natural resin/binder, as the binding agent. Standard circular specimens were fabricated using a compression molding technique. Three different ratios of fiber-to-binder were investigated: Sample A (90:10), Sample B (80:20), and Sample C (70:30). The sound absorption properties were strictly tested using the Transfer-function method (ISO 10534-2). The results demonstrated that the specimen with highest fiber loading, Sample A (90:10), exhibited the most effective acoustic performance. This optimal sample achieved a high Noise Reduction Coefficient (NRC) of 0.44 and showed maximum absorption with a Sound Absorption Coefficient (SAC) of 61.96% at a key mid-frequency of 500 Hz. The results strongly suggest that a higher proportion of bamboo leaf fiber is crucial for developing and maintaining the necessary porous structure within the composite, which facilitates effective sound dissipation. These findings demonstrate the potential of bamboo leaf composites as sustainable, cost-effective alternatives to synthetic sound-absorbing panels, successfully valorizing agricultural waste into high-value products.

Keywords: Bamboo leaves, Nature binder, Acoustic absorbers, Compression molding

1. Introduction

An extensive challenge of sustainable waste management and resource utilization is a critical issue globally, particularly concerning the vast quantities of agricultural residues generated in developing economies. In Thailand, this problem is severe within the agricultural sector, particularly in highland monoculture areas. The prevailing and often simplest disposal method-open burning-is a primary contributor to severe air pollution (PM 2.5), smog, and widespread degradation of the ecosystem, including soil, water, and forest resources. To moderate this environmental crisis, the Mae Chaem model plus project was initiated to reduce single-crop cultivation areas, curb burning practices, and promote the substitution of maize with bamboo as an economic crop. Bamboo is a fast-growing plant that requires minimal fertilizer or pesticides, offers diverse benefits across its structure, effectively sequesters carbon dioxide, and improves soil quality. The abundant seasonal leaf shedding situation underscores the urgent need for developing creative management strategies for agricultural waste. Utilizing bamboo leaves as a local resource not only helps relieve environmental problems but also generates economic value for the community. Furthermore, the development of environmentally friendly materials aligns with the Bio-Circular-Green (BCG) economy model [1] for transformative change, income generation, and sustainability, directly contributing to the Sustainable Development Goals (SDGs) [2] offering a pathway to mitigate environmental crises while generating local income. Accordingly, this research focuses on the valorization of natural waste material, specifically bamboo leaves, for the development of an acoustic absorption product for building interiors, utilizing the compression molding technology [3]. Compression molding process approach inherently aligns with the principles of eco-design [4], which mandates the use of environmentally conscious materials and production processes, and the circular economy [5], which emphasizes waste minimization and resource reuse. Economically, the potential cost reduction is substantial: the bamboo leaf acoustic material has the potential to significantly undercut the cost of synthetic fiber acoustic panels currently on the market, with an estimated production cost averaging 200 THB/m² compared to market prices often reaching 3,000 THB/m². Global research is increasingly focused on developing acoustic absorption materials from agricultural by-products such as coconut coir, kenaf fiber, rice husk, and orange peel, aiming to replace environmentally impactful synthetic fibers. The sound absorption efficacy of these porous materials is not solely determined by the material type but is primarily governed by key physical parameters: Increased thickness enhances absorption in the low-to-mid frequency ranges; higher density generally correlates with improved sound absorption; and the porous structure and air voids are crucial for improving low-frequency absorption and optimizing material usage [6]. Existing studies demonstrate a wide range of Noise Reduction Coefficient (NRC) values for natural materials, such as coconut coir (0.20-0.43) and peanut shell (0.23-0.54). The influence of internal structure is paramount, as demonstrated by studies on wood. [7] summarized acoustic performance is directly controlled by the material's anatomical features and porosity. The creation of a back air cavity can significantly increase the Sound Absorption Coefficient (SAC) in the low-frequency range, with woods like hackberry and oak achieving high NRC values (0.55 and 0.53) at a 4 cm cavity depth. This highlights that high porosity and large pore sizes enhance low-frequency sound absorption. A key challenge for natural waste materials includes inherent limitations in low-frequency absorption and concerns regarding environmental durability (moisture, decay) and fire safety. Recent innovations aim to overcome the low-frequency limitation by integrating structures like Micro-Perforated Plates (MPP) [8] into the composite structure. Despite these advancements, a significant research gap remains regarding the use of bamboo leaf waste as a primary fiber in compression-molded composites. Furthermore, while innovations like Micro-Perforated Plates (MPP) have been used to enhance low-frequency absorption, there is limited research on 100% bio-based composites that utilize natural binders.

This study addresses these limitations by developing a novel, eco-friendly acoustic panel derived from bamboo leaf powder and Persea kurzii (a natural resin). The objectives are to: 1) design and develop a sound-absorbing product from bamboo leaf composites, and 2) fabricate a specific compression molding die for its production. This research validates a method for transforming agricultural waste into a high-value green alternative for the construction industry.

2. Materials

2.1. Dried Bamboo Leaves

The dried bamboo leaves utilized in this research are agricultural residues sourced from the natural shedding of the native 'Fah Mon' bamboo species (a local variety of Dendrocalamus asper or similar giant timber bamboo). These bamboo groves are cultivated by the Pai Ngoen Lan Community Enterprise in Tha Pha subdistrict, Mae Chaem district, Chiang Mai province. This specific source is highly significant as 'Fah Mon' bamboo produces a substantial volume of waste, averaging 1,000 kg of leaves per shedding cycle annually, which is predominantly disposed of via open burning, composting, or landfilling. Figure 1(a) and (b) illustrated bamboo forest and dried bamboo leaves, respectively.


(a) (b)

Figure 1 Natural material (a) bamboo forest (b) dried bamboo leaves

The preparation process for the bamboo leaves began with collection from the research area. The collected leaves were then cleaned thoroughly to remove surface contaminants and dust. Following cleaning, the leaves were sun-dried or oven-dried at 60°C for 8 hours until 10% residual moisture to reduce the moisture content to a level appropriate for subsequent molding and processing. The dried leaves were then subjected to size reduction processes, such as shredding, milling, and grinding, to ensure a uniform particle size distribution. This consistency in particle size is crucial for achieving optimal dispersion within the binding matrix, which directly influences the final structural and acoustic properties of the product. Quality control from collection through preparation is essential to ensure consistent properties in the resulting sound-absorbing product.

2.2. Natural Binder (Bong Resin)

This research utilizes Persea kurzii powder, locally known as "Bong resin" as the natural binding agent, consistent with the objective of developing an eco-friendly product and promoting the utilization of local resources. Beyond its sustainability and bio-based origin [9], the selection of Bong resin is justified by its specific engineering properties. It contains high polysaccharide content (mucilage), which acts as a natural adhesive when activated under the heat and pressure of compression molding. This mucilage facilitates strong interfacial bonding between the bamboo leaf fibers, ensuring the structural integrity of the composite. Additionally, its inherent chemical composition provides natural resistance to termites, weevils, and ants, making it a desirable bio-based additive. Furthermore, it is compatible for blending with various natural fibers. The selection of Bong resin directly aligns with the project's goal of utilizing natural resources to create value and economic opportunities for the local community. It also supports the Bio-Circular-Green (BCG) economy concept by emphasizing the recirculation of bio-based materials. The Bong resin will be prepared and mixed with the dried bamboo leaf powder at optimized ratios. This process is crucial to ensure that the binder is uniformly distributed and provides the necessary adhesion properties for the final product's structural integrity. The optimized mixing ratio will be determined experimentally. Figure 2 (a) and (b) shows the Bong tree bark and the Bong resin powder, respectively.

(a) (b)

Figure 2 Natural binder (a) Bong tree bark (b) Bong resin powder [10]

2.3. Compression Molding

The acoustic absorbing product from the bamboo leaf fiber and natural binder will be fabricated using compression molding technique. This is a process where a material charge is subjected to a compressive force to shape it according to the geometry of the mold cavity. This method is highly suitable for natural fiber composites due to its effectiveness and, critically, the lower cost of mold creation compared to other molding techniques. The fundamental components of the mold assembly consist of an upper movable mold part (core) and a lower fixed mold part (cavity). The compressive force (F) exerted by the upper mold half squeezes the material charge, placed between the two halves, to conform to the shape defined by the mold cavity, as schematically shown in Figure 3. The compressive force required for forming the composite is calculated based on the necessary molding stress (σ). The relationship between the force, stress, and the surface area of compression is defined by Equation (1):

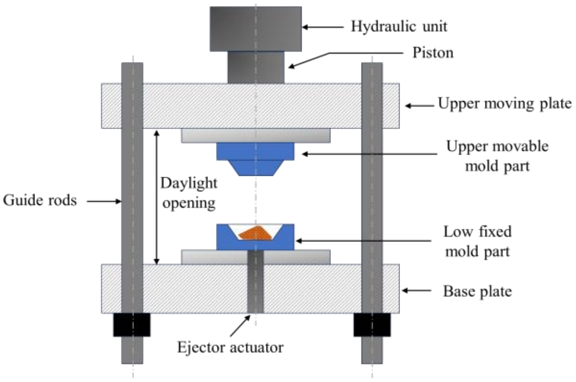


Figure 3 Schematic setup of compression molding process [11]

$$\sigma=F/A \tag{1}$$

where: σ is the stress applied to the material (N/mm^2), F is the applied force (N). A is the cross-sectional area where the force is applied (mm^2) [12].

2.4 Sound Absorption

Sound absorption is the fundamental mechanism crucial for sound energy dissipation. When sound waves strike a material, a portion of the incident energy is converted into thermal energy through various processes. The core mechanism for sound absorption in porous materials (such as natural fibers or foam) is viscous friction (or Visco-thermal damping). This occurs as air molecules oscillate and encounter resistance within the tortuous, open-pore structure of the material. This restricted movement of air within small cavities results in the transfer of the sound wave's kinetic energy into heat, thereby attenuating the acoustic energy. The sound absorption performance of a material is quantified by the sound absorption coefficient (α) at specific frequencies. An important average measure is the Noise Reduction Coefficient (NRC), which is the arithmetic average of (α) at the principal speech frequencies (250, 500, 1000, and 2000 Hz). The essential physical parameters influencing the material's absorption efficiency include: optimal thickness, density, and open porosity structure (This is arguably the most critical factor, as it dictates the airflow resistivity and the internal surface area available for viscous friction.) [13]. The sound absorption properties in this research were measured according to ISO 10534-2: Acoustics - Determination of sound absorption coefficient and impedance in impedance tubes - Part 2: Transfer-function method [14]. This standard provides a method for determining the normal incidence sound absorption coefficient (α_n) and the surface acoustic impedance using an impedance tube (or Kundt's tube) [15-16]. The sound absorption coefficient (α) is calculated using Equation 2 [17].

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

where: (α) is the sound absorption coefficient ($0 \leq \alpha \leq 1$). $|R|^2$ is the magnitude squared of the reflection coefficient, which signifies the proportion of acoustic energy reflected back. The complex acoustic transfer function (H_{12}) between microphone 1 and microphone 2 is defined in Equation 3 [2.5.1-2]:

$$H_{12}=\frac{P_2}{P_1}=\frac{e^{-jkx_1}+R_p e^{jkx_2}}{e^{-jkx_2}+R_p e^{jkx_1}} \tag{3}$$

where: H_{12} is the complex acoustic transfer function between microphones 1 and 2. P_1 and P_2 are the complex sound pressures measured at the positions of microphone 1 and 2, respectively. k represents wavenumber (m^{-1}), when; $k=\frac{\omega}{c_0}=2\pi f/c_0$, which ω is the angular frequency (rad/s), c_0 is the speed of sound in air inside the room (m/s), f is the frequency (Hz), x_1, x_2; the distance from the test surface to microphone 1 and microphone 2, respectively (m), R_p is the normal-incidence pressure reflection factor (also known as the reflection coefficient). The scheme of two-microphone transfer function method can be shown in Figure 4.

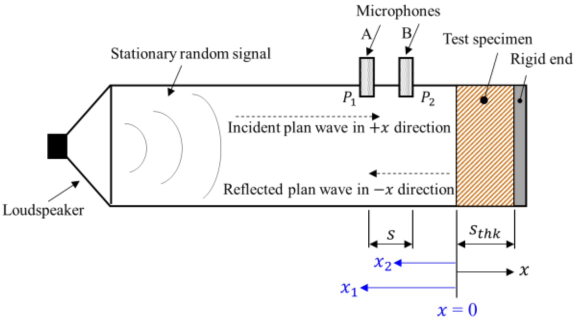
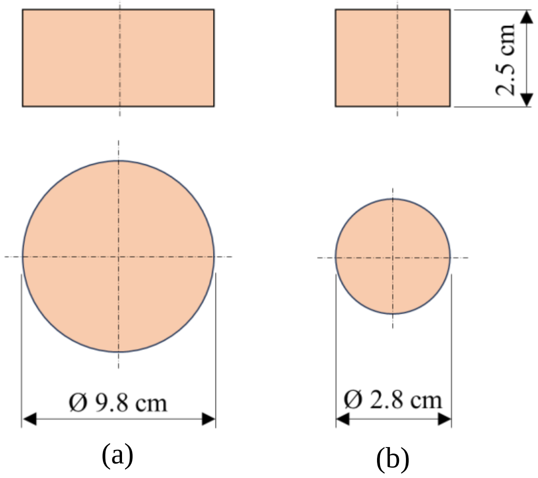


Figure 4 Scheme of two-microphone transfer function method [14]

2.5 Specimen Preparation for Sound Absorption Testing

Specimens for determining the Noise Reduction Coefficient (NRC) were prepared according to the ISO 10534-2 standard (Transfer-function method). The specimens were molded into a cylindrical shape with a uniform thickness of 2.5 cm. To cover the required range of sound frequencies for testing, two different specimen diameters were prepared for use with the appropriate impedance tube sizes. Large diameter specimen 9.8 cm used for the low-frequency zone (up to 1,600 Hz), covering the primary speech frequencies. Small diameter specimen 2.8 cm used for the high-frequency zone (1,600-4,000 Hz). The final composite panels, created using the compression molding method, were cut into these precise cylindrical dimensions to ensure an accurate fit within the impedance tube fixtures, as shown in Figure 5 (a) and (b).



(a) (b)

Figure 5 Specimen dimension [18] (a) low-sensitivity zone testing (b) high-sensitivity zone testing

3. Methods and Experimental Procedure

The experimental investigation followed the systematic procedure outlined in the flowchart shown in Figure 6. The methodology can be categorized into three main stages: (1) material preparation for both bamboo fiber and binder, (2) mixing ratio, and (3) compression of materials.

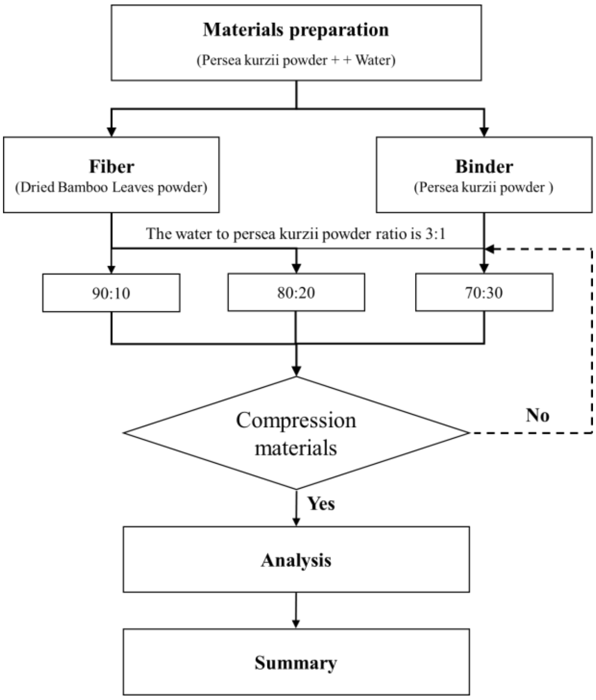


Figure 6 Methodology schematic

3.1 Material Preparation

The material preparation process was conducted to transform raw bamboo residues into a consistent natural fiber powder. The procedure consisted of the following stages: (1) Drying and Grinding: Collected dry bamboo leaves were oven-dried at 60°C for 8 hours to eliminate residual moisture until a stable moisture content of 10% and prevent biological degradation. The dried leaves were then mechanically ground using a high-speed grinder to reduce the fiber size. (2) Sieving and Particle Size Selection: To ensure a uniform internal structure within the composite, the resulting powder was sieved using a U.S. Standard Sieve No. 4, which corresponds to a mesh opening of 4.75 mm. This sieving process is critical for controlling the aspect ratio of the fibers and ensuring consistent void distribution within the final acoustic panel. (3) Final Material Formulation: The fraction passing through the sieve was collected as the primary bamboo leaf powder. This specific particle size (≤ 4.75 mm) was selected to provide an optimal balance between fiber surface area for binder adhesion and the formation of interconnected pores necessary for sound wave dissipation. The prepared bamboo leaf powder, as shown in Figure 7, was subsequently blended with the natural binder at the specified experimental ratios.

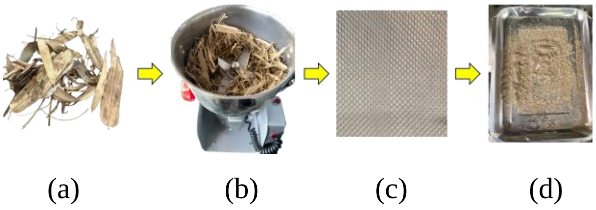

(a) (b) (c) (d)

Figure 7 Material Preparation (a) Dried bamboo leaves (b) Bamboo leaves grinding (c) Sieve no.4 (d) Bamboo leaves powder

Prepared bamboo leaf powder was subsequently mixed with Persea kurzii powder (natural binder) and water. The components were thoroughly mixed to achieve a homogeneous mixture. The main mixing ratios established between the dry bamboo leaf powder and the Persea kurzii powder were investigated at three levels (fiber: binder), ensuring a total of 100 parts; 90:10, 80:20, and 70:30. Furthermore, the amount of water added during the mixing process was determined based on the quantity of the Persea kurzii powder (binder) at a ratio of 3:1 (water: natural binder). The resulting mixture is demonstrated in Figure 8.

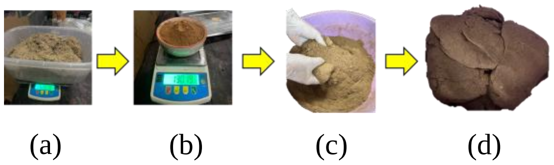

(a) (b) (c) (d)

Figure 8 Mixing Process (a) Bamboo powder weighing (b) Persea kurzii powder weighing (c) Mixing (d) Moldable Material

3.2 Compression Molding Process

Acoustic absorbing panels were fabricated using a controlled compression molding process. The following equipment and specifications were utilized; Ward-Forsyth VO30E/10 hydraulic press machine with Maximum Opening Distance 400 mm. Working table dimensions 460 mm x 500 mm. Maximum compressive force is 60 Ton. The hydraulic press, as shown in Figure 9, was used to apply a predefined pressure to the mixed bamboo leaf and binder compound inside the molds, enabling the consolidation of the composite specimens.

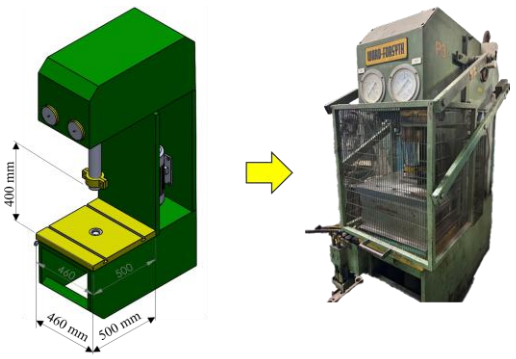


Figure 9 Ward-Forsyth VO30E/10 hydraulic press machine

The acoustic panel was fabricated using a specially designed compression mold with dimensions of 450 x 500 x 300 mm. The mold operates based on uniaxial compression principle, where the pressing force is applied in a vertical, top-to-bottom direction to densify the composite mixture into the final product shape, as shown in Figure 10.

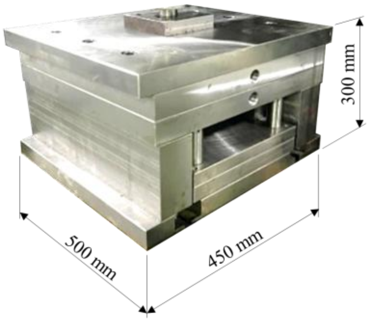


Figure 10 Compression molding

3.3 Experimental Testing

The experimental testing of the fabricated acoustic panels was divided into two main parts. To ensure methodological robustness and data reliability, all tests were performed in triplicate (n=3 per fiber-to-binder ratios per size), and the mean values were reported.

3.3.1 Specimens for Sound Absorption Testing and Noise Reduction Coefficient (NRC) Determination

Specimens for sound absorption testing were designed in accordance with the ISO 10534-2 standard (Transfer-function method). Specimen Configuration: Cylindrical specimens were fabricated in two different diameters: 9.8 cm (for low-to-mid frequency range) and 2.8 cm (for high frequency range), each having a uniform thickness of 2.5 cm. These specimens were specifically sized to fit the impedance tube apparatus. The dimensions and setup are illustrated in Figure 11.

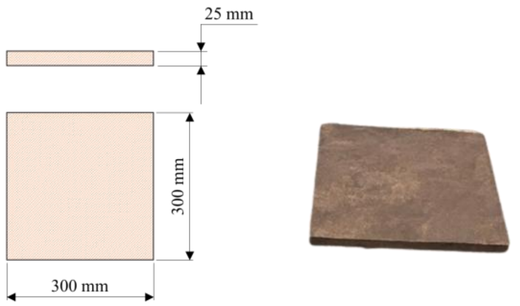
(a) (b)

Figure 11 Acoustic absorption test specimens (ISO 10534-2) (a) Specimen with a diameter of 9.8 cm (b) Specimen with a diameter of 2.8 cm

Experimental Control: The specimens were precisely machined to ensure a tight fit within the impedance tube, minimizing acoustic leakage. Ambient temperature and humidity were monitored and kept constant during the measurements to eliminate environmental interference with the sound speed. Data Reliability: For each material composition, three independent specimens were tested. The results were averaged to determine the Sound Absorption Coefficient and the Noise Reduction Coefficient (NRC), ensuring that the data were representative and reproducible.

3.3.2 Final Acoustic Panel Fabrication

The final acoustic panel was designed with nominal dimensions of 300 mm x 300 mm x 25 mm (WxLxH). The required compression force (F) for panel molding was calculated based on the following relationship: $F = \sigma$ x A where; F is the Compression Force required for forming the specimen (N). σ is the Material Stress (or required molding pressure) applied to the material. A is the Cross-sectional Area of the material (m^2). Process Control and Consistency: To strengthen the methodological robustness, the calculated compression force was maintained at 21,567 N (approximately 21.6 kgf.). Other critical process variables, including the molding temperature and the holding time (dwell time), were strictly controlled and kept uniform for every panel produced. This consistency ensures that the physical properties of the panels are directly comparable across different material ratios. The complete molding setup is illustrated in Figure 12.



(a) (b)

Figure 12 Final design and fabricated prototype (a) Schematic of the acoustic panel design (b) Final compression-molded acoustic panel

4. Results

4.1 Sound Absorption Coefficient (SAC) and Noise Reduction Coefficient (NRC)

The acoustic absorption properties of the developed sound-absorbing panels-fabricated from dry bamboo leaf powder and Bong Resin (Persea kurzii powder) via the Compression Molding technique-were evaluated in accordance with the ISO 10534-2: Transfer-Function Method standard. All tests were conducted at the Center for Building Innovation and Technology (CBIT). To ensure the statistical reliability of the data, each sample was tested in triplicate, and the mean values are presented in Table 1 and Figure 4.1The specimens were categorized into three groups based on the ratio of dry bamboo leaf powder to Bong Resin (Fiber: Binder): Sample A (90:10), Sample B (80:20), and Sample C (70:30).

Table 1 SAC and NRC values for the developed acoustic panels at varying fiber-to-binder ratios.

Samples	**A**	**B**	**C**
Type	(90:10)	(80:20)	(70:30)
250 Hz. (SAC)	30.44 %	31.78 %	18.34 %
500 Hz. (SAC)	61.96 %	41.51 %	39.50 %
1000 Hz. (SAC)	46.93 %	35.99 %	48.60 %
2000 Hz. (SAC)	37.79 %	38.37 %	35.98 %
Average (SAC)	44.28 %	36.91 %	35.60 %
NRC*	0.4428	0.3691	0.3560

Remark: The Noise Reduction Coefficient (NRC) is defined as the arithmetic average of the sound absorption coefficients (α) measured at the four standard one-third octave band center frequencies: 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz.

4.2 Analysis of Sound Absorption Performance

4.2.1 Porosity and Structural Influence on SAC

Sample A (90:10) exhibited the highest NRC of 0.44, with a peak SAC of 61.96% at 500 Hz. From a structural perspective, the high fiber-to-binder ratio in Sample A maintains a high volume of interconnected open pores. When sound waves enter this porous matrix, acoustic energy is dissipated through two primary mechanisms:

(1) Viscous Losses: The friction between the oscillating air molecules and the complex cell wall structures of the bamboo leaf powder.

(2) Thermal Dissipation: The conversion of sound energy into heat as the pressure fluctuations interact with the large internal surface area of the fiber network. The peak at 500 Hz suggests that the pore size distribution and the thickness of the panel (25 mm) are optimally tuned to the wavelength of mid-frequency sound, providing maximum flow resistance in this range.

4.2.2 Impact of Binder Concentration on Tortuosity and Flow Resistance

As the proportion of the Persea kurzii powder (Bong Resin) binder was increased-from 10% in Sample A, 20% in Sample B, to 30% in Sample C-the corresponding Noise Reduction Coefficient (NRC) showed a consistent decline in NRC (0.443, 0.369, and 0.356, respectively). This trend can be explained by the mechanical filling effect of the binder:

(1) Pore Blockage: The increased binder volume fills the interstitial spaces between bamboo fibers, reducing the effective porosity of the material.

(2) Increased Tortuosity: As pores become clogged, the paths for sound wave penetration become more restricted or closed. While a certain level of tortuosity is beneficial, an excess of binder (as seen in Sample C) leads to a "closed-pore" structure, reflecting sound waves rather than absorbing them.

(3) Mechanical Rigidity: Higher binder content increases the structural stiffness of the panel. From a mechanical evaluation standpoint, a more rigid and less permeable matrix reduces the membrane-like vibration of the fibers, which otherwise contributes to low-to-mid frequency absorption.

4.2.3 Statistical Significance and Trend Analysis

The downward trend in NRC relative to binder concentration (A > B > C) indicates a strong correlation between binder ratio and acoustic impedance. Statistical evaluation suggests that the

10% binder threshold is critical; exceeding this limit results in a significant loss of mid-frequency absorption (a 33% drop at 500 Hz from Sample A to B). This confirms that Sample A (90:10) achieves the optimal balance between structural integrity (mechanical bonding) and acoustic permeability.

5. Conclusion

This research successfully designed and developed a bio-based sound-absorbing product utilizing agricultural waste. The material was fabricated using dry bamboo leaves sourced from the local “Fah Mon" bamboo species in Mae Chaem District, Chiang Mai, combined with Bong Resin (a natural binder), through a compression molding process. The developed acoustic panel demonstrated the highest sound absorption efficiency at the 90:10 ratio of dry bamboo leaf powder to Bong Resin (Sample A). This optimal formulation yielded a high Noise Reduction Coefficient (NRC) of 0.44, which is suitable for use as non-structural acoustic material in building applications, with its peak performance reaching 61.96% Sound Absorption Coefficient at 500 Hz. Experimental results clearly indicate that the proportion of dry bamboo fiber is the primary factor influencing sound absorption performance. The high fiber content effectively preserves the porous structure necessary for sound energy dissipation by maximizing the frictional resistance of air molecules. Conversely, increasing the quantity of Bong Resin binder led to a reduction in the measured NRC values. Ultimately, this work successfully applies manufacturing technology to valorize agricultural residues (specifically, up to 1,000 kg of bamboo leaves per cycle per year) into a high-value product. This initiative strongly aligns with the Bio-Circular-Green (BCG) Economy model and the Sustainable Development Goals (SDGs), particularly by mitigating the severe environmental issue of open burning and creating economic value for local communities. While this study provides a successful proof-of-concept for bamboo-leaf-based acoustic panels, certain limitations remain to be addressed in future work: Mechanical and Durability Testing: This study focused primarily on acoustic performance. Future research should evaluate the mechanical properties, flammability and biological resistance, as well as scale-up and transmission loss.

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