

# Innovative Approaches to Sound Absorption in Agricultural Waste-Based Composites: The Role of Perforation Geometry

## Ilham Bakri

Department of Industrial Engineering, Hasanuddin University, Makassar, Indonesia | Health and Safety Engineering Research Group, Hasanuddin University, Makassar, Indonesia  
ilhambakri@unhas.ac.id (corresponding author)

## Fatimah Sahra Musafir

Department of Industrial Engineering, Hasanuddin University, Makassar, Indonesia  
fatimahsahramusafir@gmail.com

## Kifayah Amar

Department of Industrial Engineering, Hasanuddin University, Makassar, Indonesia  
kifayah.amar@unhas.ac.id

## Asniawaty Kusno

Department of Architecture, Hasanuddin University, Makassar, Indonesia  
asniawaty@unhas.ac.id

## Rizki Nur Fadhilah

Department of Architecture, Hasanuddin University, Makassar, Indonesia  
fadhillahrn21d@student.unhas.ac.id

Received: 4 September 2025 | Revised: 30 September 2025 | Accepted: 10 October 2025

Licensed under a CC-BY 4.0 license | Copyright (c) by the authors | DOI: <https://doi.org/10.48084/etasr.14540>

## ABSTRACT

This study explores the potential of agricultural waste-based composites, specifically sugarcane bagasse, as sustainable sound-absorbing materials. The research investigates the impact of partial perforations on the Sound Absorption Coefficient (SAC) of bagasse-based panels, with perforation diameters of 1, 2, and 3 mm and depths of 25%, 50%, 75%. Acoustic performance was evaluated using an impedance tube across the frequency range of 200–1600 Hz. The results reveal that panels with 1 mm diameter perforations and 75% depth exhibited the highest SAC, reaching up to 0.98 at 1500–1600 Hz. These findings underscore the potential of perforation geometry as a key factor in enhancing the acoustic efficiency of bio-composite materials. This study highlights the viability of optimizing perforation designs to develop sustainable, high-performance sound absorbers, offering an eco-friendly alternative to conventional acoustic materials. The outcomes contribute to advancing circular economy practices by utilizing agricultural waste for noise mitigation in urban environments.

*Keywords-sustainable composites; sound absorption; agricultural waste; sound absorption coefficient; perforated bio-composites*

## I. INTRODUCTION

Environmental noise pollution is a significant and growing global challenge, with particularly severe consequences for urban and developing areas. According to the World Health Organization (WHO), noise pollution is one of the most pressing environmental risks, second only to air pollution, and it is responsible for a range of adverse health effects, including

stress, sleep disturbances, cardiovascular diseases, and mental health issues [1]. In cities and densely populated regions, where industrial activity, transportation, and other anthropogenic factors are prevalent, the detrimental effects of noise on human health are exacerbated. Research has confirmed the urgency of addressing noise as a critical environmental hazard, given its increasing impact on public health [2]. The health implications

of noise pollution are wide-ranging, and the need for effective noise control measures has never been more critical.

Long-term exposure to elevated noise levels has been associated with various cardiovascular disorders, including hypertension, heart attacks, and even premature mortality. Furthermore, noise pollution has a direct effect on cognitive development and performance in children and adults, impacting learning, memory, and overall productivity [1]. Given the ubiquity of noise in modern life, finding sustainable solutions to mitigate its impact has become an essential part of urban planning and public health policies.

Traditional materials used for sound absorption, such as synthetic foams and mineral wool, have been effective in controlling noise, but they come with significant environmental and health drawbacks. These materials are typically derived from petrochemical-based sources, making them non-biodegradable and contributing to environmental degradation when disposed of at the end of their life cycle. The production of synthetic sound absorbers also generates substantial emissions and contributes to the depletion of natural resources, raising concerns about their sustainability. As a result, there is an increasing need for alternative, environmentally friendly sound-absorbing materials that can address both the acoustic and environmental challenges posed by traditional materials.

There has been growing interest in the use of natural fiber-based composites as sustainable alternatives for sound absorption. Materials derived from agricultural waste, such as sugarcane bagasse, have shown promise in this regard. These materials offer the potential for comparable acoustic performance to conventional synthetic absorbers while being biodegradable and less harmful to the environment [3-5]. The use of agricultural by-products for the development of bio-based composites aligns with the global push toward sustainability and circular economy practices, wherein waste materials are reused to create valuable resources. Moreover, sugarcane bagasse, a widely available agricultural by-product, can replace synthetic materials in various applications, reducing dependence on finite resources and supporting sustainable development [3].

The morphology of plant-based composites plays a crucial role in determining their acoustic performance. The porosity and alignment of fibers within the composite material are factors that influence its ability to absorb sound [6, 7]. Increased porosity allows sound waves to penetrate the material more easily, where they are then dissipated as heat through viscous interactions. Furthermore, optimizing fiber alignment can enhance the material's ability to dissipate sound energy, improving its overall acoustic properties. Techniques, such as additive manufacturing, have enabled the precise control of fiber alignment and porosity, allowing for the creation of complex geometries that further enhance the acoustic performance of these materials [8, 9].

Several fabrication techniques are commonly employed in the development of bio-composite acoustic panels. Hand lay-up and compression molding are two such methods that affect the performance of the material by influencing fiber distribution and matrix connectivity. Hand lay-up is a relatively simple and

adaptable method that allows for uniform fiber distribution and effective resin impregnation [10]. This technique has been shown to result in superior control over the material's structure, ensuring that the desired acoustic properties are achieved. In contrast, compression molding, while more complex, typically yields stronger mechanical properties due to better fiber alignment and increased density [11]. The choice of fabrication method is crucial in determining the acoustic properties of bio-composite panels, as uniform fiber distribution and proper resin impregnation are essential for optimizing sound absorption.

The geometric configuration of the material, including perforation size and panel shape, also plays a critical role in enhancing acoustic performance. Perforated panels have been found to improve sound absorption by allowing sound waves to enter the material more effectively and dissipate energy through air friction and viscous damping [12]. The size and distribution of perforations in the panel affect its performance at different frequencies. For example, panels with small perforations are more effective at absorbing high-frequency sounds, while larger perforations are better suited for low-frequency noise. The arrangement of perforations within the panel can also influence its overall acoustic behavior, with certain patterns optimizing absorption across a broad range of frequencies.

This study aims to investigate the effect of partial perforations on the sound absorption characteristics of sugarcane bagasse-based composites. While the use of perforations in porous materials to enhance acoustic performance is well-established, the specific impact of perforation patterns on the properties of natural fiber composites, especially those derived from agricultural waste, remains underexplored [13, 14]. By focusing on the microstructural complexities of sugarcane bagasse composites, the present study seeks to provide an understanding of how varying perforation designs can optimize the acoustic performance of these sustainable materials.

In addition to improving the sound absorption performance, the reuse of agricultural waste, such as sugarcane bagasse, aligns with the principles of the circular economy. Agricultural waste, often discarded or burned, can be transformed into valuable materials that contribute to both environmental sustainability and economic development [15, 16]. This approach not only reduces waste but also minimizes the environmental impact of traditional noise-control materials, thereby contributing to the broader goal of sustainable material development [17].

The potential applications of bio-based sound absorbers in urban planning, construction, and noise mitigation are vast. The incorporation of natural fiber-based panels, such as those made from sugarcane bagasse, into building designs can help manage noise pollution, improve the quality of urban living, and contribute to energy efficiency [4, 18]. These materials are not only effective in controlling noise but also provide economic benefits by reducing energy consumption through enhanced thermal insulation properties. Moreover, the adoption of sustainable acoustic materials supports public health by mitigating the negative effects of noise-related stress and annoyance [19].

This research introduces partial perforations directly into a porous, bagasse-based bio-composite instead of using a rigid perforated facing above an air cavity. It systematically decouples the roles of hole diameter and partial depth through a factorial design methodology. This 'in-material' perforation strategy for agricultural-waste panels is relatively underexplored in comparison to Micro-Perforated Panel (MPP) facings and traditional Helmholtz-type designs. This study quantified the effects of millimetric apertures on flow resistivity pathways and high-frequency dissipation in a biodegradable composite. However, it has not addressed practical considerations for scale-up, including repeatable drilling and punching, durability in terms of moisture and fire behavior, and benchmarking against conventional foams and mineral wool.

## II. MATERIALS AND METHODS

For this study, sugarcane bagasse, an abundant agricultural by-product from the sugar industry, was selected as the primary raw material for the sound-absorbing composite panels. The bagasse was sourced from Arasoe Sugarcane Plant, Bone, South Sulawesi, Indonesia. Bagasse is rich in cellulose, hemicellulose, and lignin, which makes it a suitable candidate for use in bio-composites (Figure 1). The fibers were first subjected to a chemical treatment to remove impurities and to improve fiber-matrix bonding. A 5% sodium hydroxide (NaOH) solution was used for the alkali treatment, a well-established method for enhancing the surface properties of lignocellulosic fibers. NaOH treatment has been reported to increase fiber surface roughness and improve the interface between the fibers and the resin matrix [20, 21]. Following treatment, the fibers were dried at ambient temperature for 8 h to remove excess moisture before being used in the composite preparation.



Fig. 1. Bagasse from Arasoe Sugarcane Plant, Bone, South Sulawesi, Indonesia.

The composite panels were fabricated deploying the hand lay-up technique, a widely employed method for manufacturing bio-based composites, due to its simplicity and versatility [10]. In this study, the bagasse fibers were mixed with a polyester resin at a weight ratio of 60:40, which is considered optimal for balancing the mechanical strength and acoustic performance in bio-composites [11]. The polyester

resin utilized was unsaturated, with a specific gravity of 1.215 g/cm<sup>3</sup>, and a 1% catalyst was added to initiate the curing process.

The fibers and resin were thoroughly mixed to ensure uniform distribution of the fibers throughout the matrix. After mixing, the composite material was poured into cylindrical molds with a diameter of 100 mm and a thickness of 30 mm, which is the standard size for acoustic testing in impedance tubes [22]. The molds were coated with a non-stick substance to facilitate the removal of the cured samples. The composites were then allowed to cure at room temperature for 24 h, after which they were demolded and prepared for further processing (Figure 2).



Fig. 2. Bagasse composite and sample preparation.

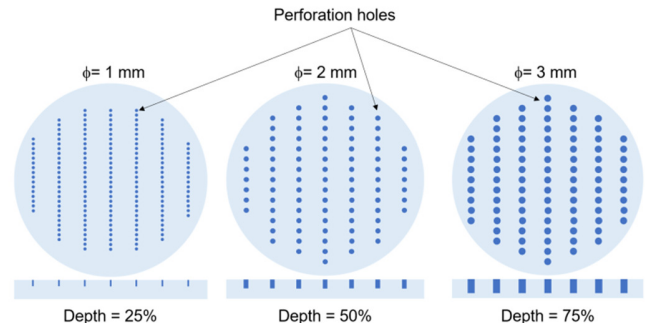


Fig. 3. Partial perforation design on samples.

After curing, the composite panels were carefully removed from the molds. To enhance their acoustic performance, partial perforations were introduced to the panels using an electric drill. The perforation sizes were varied, with diameters of 1 mm, 2 mm, and 3 mm, and depths set at 25%, 50%, and 75% of the panel thickness (Figure 3). The perforation patterns (Figure 4) were designed to disrupt the normal reflection of sound waves and enhance sound absorption by introducing additional paths for sound energy dissipation [12, 13]. The perforations were made using a drill template to ensure consistent and precise hole placement across all samples. The final dimensions of the prepared samples were 100 mm in diameter and 30 mm in thickness, with the perforations evenly distributed across the surface. These samples were then subjected to acoustic testing (Figure 5).

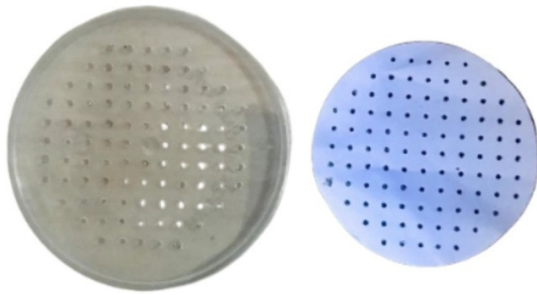


Fig. 4. Perforation template.

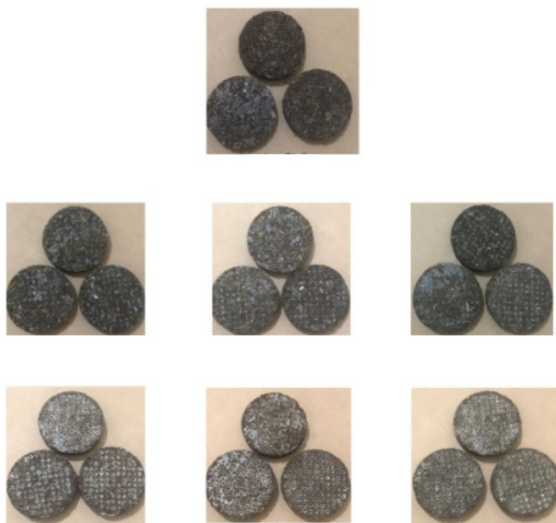


Fig. 5. Partial perforated bagasse composite samples.

The sound absorption properties of the composite panels were evaluated using the two-microphone impedance tube method, in accordance with ASTM E1050-98 standards [24]. This method is commonly employed to assess the SAC of small-sized materials, yielding dependable results within the frequency range of 200 Hz to 1600 Hz [25]. Frequencies were selected based on the utilization of the Brüel & Kjaer 4206 type impedance tube employed in this study. The 100 mm tube of the Brüel & Kjaer Type 4206 system is designed for accurate plane-wave, normal-incidence measurements up to 1.6 kHz. However, below approximately 200 Hz, the signal-to-noise and edge-leakage effects may become significant for 30 mm samples [24, 26]. The apparatus consisted of two ¼-inch condenser microphones (Type 4187), an amplifier (2716C), and the PULSE system for signal processing and data acquisition.

The SAC was determined by measuring the incident and reflected sound waves as they interacted with the material. The samples were positioned inside the impedance tube, and the sound waves were generated by a loudspeaker placed at one end of the tube (Figure 6). The microphones recorded the sound pressure levels at two points, allowing the software to calculate the SAC at various frequencies. Each sample was tested three times to ensure the repeatability of the results.

The acoustic data were statistically analyzed using Two-Way Analysis of Variance (ANOVA) to evaluate the significance of the perforation diameter and depth in the SAC. This analysis was performed to determine if the main effects of perforation diameter and depth, as well as their interaction, significantly influenced the sound absorption performance. A significance level of  $p < 0.05$  was considered for all statistical tests. The design was based on a 3x2 factorial arrangement, where three levels of perforation diameter (1 mm, 2 mm, 3 mm) and three levels of perforation depth (25%, 50%, 75%) were considered (Table I). The ANOVA results were followed by post-hoc pairwise comparisons to further explore the differences between the groups when significant effects were found. All statistical analyses were performed using standard statistical software, and the results were presented as mean values with standard deviations to show the variability across the samples.

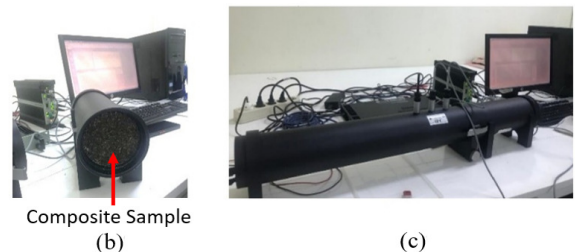
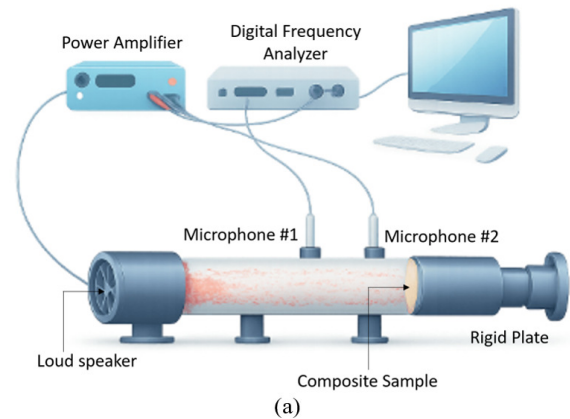


Fig. 6. SAC measurement: (a) equipment scheme, (b) sample on the tube, (c) measurement process.

TABLE I. FACTORIAL DESIGN MATRIX 32

Factor	Symbol	Units	Levels		
			-1	0	1
Perforation diameter	X1	mm	1	2	3
Perforation depth	X2	%	25	50	75

### III. RESULTS

#### A. Sound Absorption Coefficient of the Composite Samples

The SAC of the sugarcane bagasse-based composite panels was evaluated across the frequency range of 200 Hz to 1600 Hz. The results revealed that the SAC values of the composite panels varied significantly depending on the perforation

diameter and depth. As shown in Table II, the SAC values for the untreated composite (flat) ranged from 0.03 to 0.44 across the tested frequencies. In contrast, the perforated panels demonstrated a marked improvement in SAC, with values ranging from 0.05 to 0.98, depending on the perforation parameters.

In general, samples with a perforation diameter of 1 mm and a perforation depth of 75% achieved the highest SAC

values, with a peak of 0.98 at frequencies between 1500 Hz and 1600 Hz, as displayed in Figure 7(a). This indicates that small perforations (1 mm) with deep perforation (75%) significantly enhance the sound absorption performance, especially at high frequencies. Similar trends were observed for panels with 2 mm and 3 mm perforations, although the SAC values for the 3 mm perforations were lower, particularly at the lower frequencies, as illustrated in Figures 7(b) and 7(c).

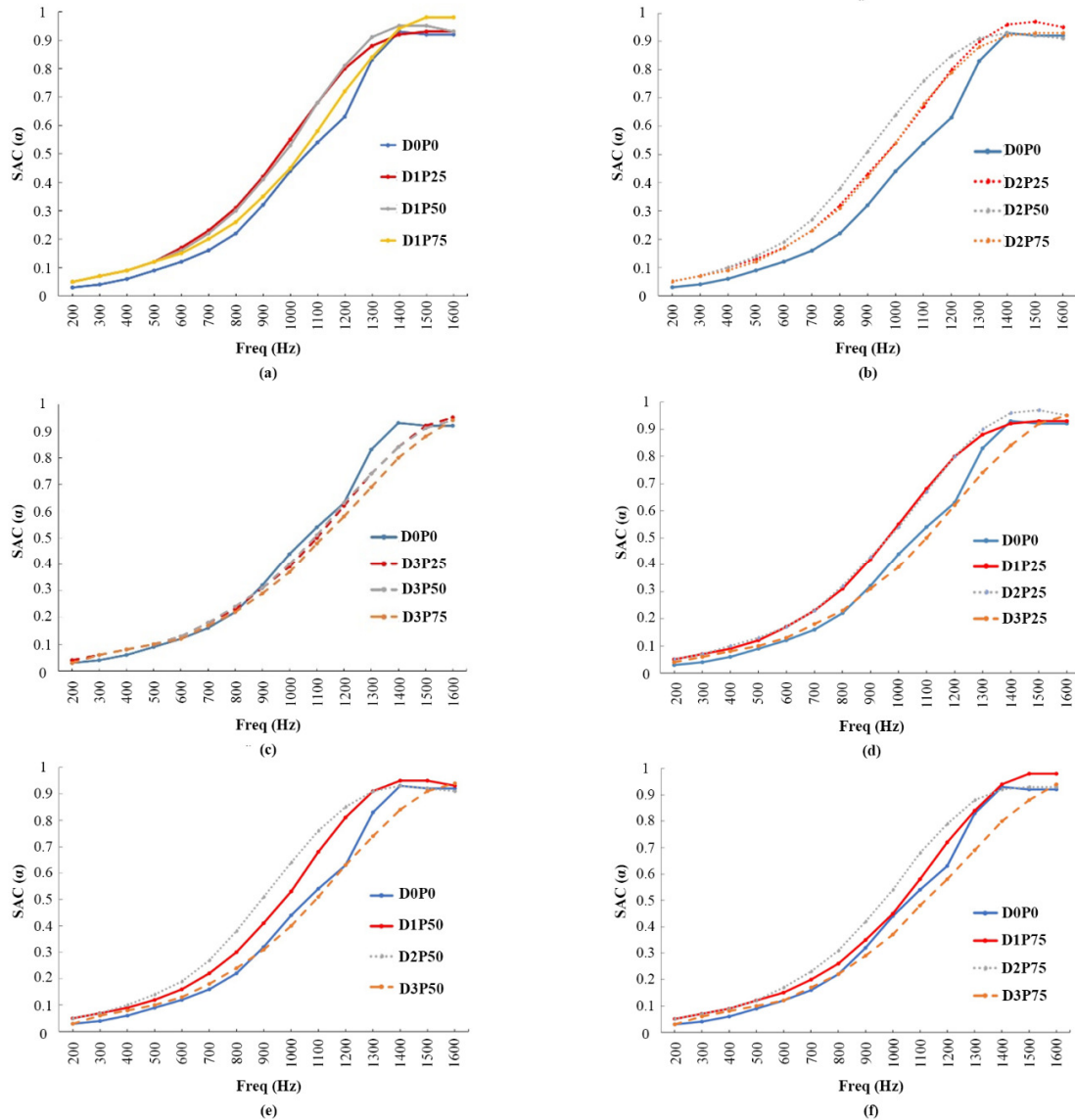


Fig. 7. The SAC: (a) different perforation with 1 mm diameter, (b) different perforation with 2 mm diameter, (c) different perforation with 3 mm diameter, (d) different diameter with 25% perforation, (e) different diameter with 50% perforation, (f) different diameter with 75% perforation.

TABLE II. THE SAC

Frequency (Hz)	SAC ( $\alpha$ )									
	Flat	1 mm			2 mm			3 mm		
		D0P0	D1P25	D1P50	D1P75	D2P25	D2P50	D2P75	D3P25	D3P50
200	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.03	0.03
300	0.04	0.07	0.07	0.07	0.07	0.07	0.07	0.06	0.06	0.06
400	0.06	0.09	0.09	0.09	0.10	0.10	0.09	0.08	0.08	0.08
500	0.09	0.12	0.12	0.12	0.13	0.14	0.12	0.10	0.10	0.10
600	0.12	0.17	0.16	0.15	0.17	0.19	0.17	0.13	0.13	0.12
700	0.16	0.23	0.22	0.20	0.23	0.27	0.23	0.18	0.18	0.17
800	0.22	0.31	0.30	0.26	0.32	0.38	0.31	0.23	0.24	0.22
900	0.32	0.42	0.41	0.35	0.43	0.51	0.42	0.31	0.31	0.29
1000	0.44	0.55	0.53	0.45	0.54	0.64	0.54	0.39	0.40	0.37
1100	0.54	0.68	0.68	0.58	0.67	0.76	0.68	0.50	0.51	0.48
1200	0.63	0.80	0.81	0.72	0.80	0.85	0.79	0.62	0.63	0.58
1300	0.83	0.88	0.91	0.84	0.90	0.91	0.88	0.74	0.74	0.69
1400	0.93	0.92	0.95	0.94	0.96	0.93	0.92	0.84	0.84	0.80
1500	0.92	0.93	0.95	0.98	0.97	0.92	0.93	0.92	0.91	0.88
1600	0.92	0.93	0.93	0.98	0.95	0.91	0.93	0.95	0.94	0.94

### B. Effect of Perforation Diameter on SAC

The results indicate that the perforation diameter plays a significant role in enhancing the acoustic performance of the composite panels. Panels with a perforation diameter of 1 mm exhibited the highest SAC, especially at mid to high frequencies (1000 Hz to 1600 Hz). Figures 7(b) and 7(c) show that as the perforation diameter increased to 2 mm and 3 mm, the SAC values decreased, particularly at lower frequencies.

These findings are consistent with those in [23, 27], where it was reported that smaller perforations lead to better sound absorption at higher frequencies due to enhanced interaction between the sound waves and the material. Moreover, the results suggest that an optimal perforation diameter of 1 mm maximizes the absorption of sound waves, particularly at mid-range frequencies, which is/are the most common range of environmental noise.

### C. Effect of Perforation Depth on SAC

The depth of perforation also significantly influenced the SAC values. As shown in Figure 7, increasing the perforation depth from 25% to 75% improved the SAC across all perforation diameters. The 75% perforation depth yielded the highest SAC, particularly for 1 mm and 2 mm perforations. Panels with a perforation depth of 75% exhibited SAC values approaching 1.0 at frequencies between 1500 Hz and 1600 Hz, which indicates nearly perfect sound absorption at these frequencies, as shown in Figure 7(a).

In comparison, Figure 7(d) demonstrates that panels with a perforation depth of 25% exhibited lower SAC values, particularly at lower frequencies. This observation supports the findings from [23, 28], where it was suggested that deeper perforations allow for better sound wave penetration into the material, thereby increasing the dissipation of sound energy through viscous damping and thermal conversion.

### D. SAC Comparison for Different Perforation Configurations

The highest overall SAC was observed in the composite panel with 1 mm perforations and a 75% perforation depth, followed by 2 mm perforations with a 75% perforation depth.

The samples with 3 mm perforations generally displayed lower SAC values across all frequencies, indicating that larger perforations may reduce the material's ability to absorb sound effectively, particularly at lower frequencies.

These results align with those in [29-31], where it was shown that aperture geometry must be optimized to trade off enhanced wave-material interaction against panel integrity and pore-network continuity [29]. Excessively large perforations may disrupt the internal pore structure, reducing the overall effectiveness of the material in absorbing sound [30, 31].

### E. Frequency-Specific Performance

The SAC performance at various frequencies showed that the composite panels with small perforations (1 mm and 2 mm) excelled in the mid to high-frequency range (1000 Hz-1600 Hz). For instance, panels with 1 mm perforations and 75% depth achieved peak SAC values of 0.98 at 1500 Hz and 1600 Hz, as Figure 7(a) depicts. However, Figure 7(d) shows that at low frequencies (200 Hz-600 Hz), the SAC was lower, with values ranging from 0.03 to 0.1, indicating less effective absorption at lower frequencies.

This frequency-specific behavior is consistent with [32, 33], where it was reported that natural fiber composites and perforated panels typically perform better at higher frequencies, where the sound wave interaction with the material is more effective. To enhance low-frequency absorption, modifications such as increasing panel thickness or adjusting pore structures have been proposed [32, 34].

### F. Interaction between Perforation Diameter and Depth

Two-way ANOVA was performed to analyze the effect of perforation diameter and depth on the SAC. The results indicated that both the perforation diameter ( $p < 0.01$ ) and perforation depth ( $p < 0.05$ ) had a statistically significant effect on the SAC. The interaction between the perforation diameter and depth was found to be significant ( $p < 0.05$ ), suggesting that the optimal acoustic performance is achieved when both parameters are considered together. Post-hoc comparisons further revealed that panels with 1 mm perforations and 75%

depth significantly outperformed other configurations in terms of SAC at mid to high frequencies.

In comparison, perforated bagasse panels of similar thickness (optimal case: 1 mm/75% depth) attained a SAC of approximately 0.98 at frequencies of 1.5–1.6 kHz, demonstrating competitiveness with commercial melamine (Basotect) foam (25 mm thickness). Basotect exhibits random incidence absorption coefficients of approximately 0.70 at 1 kHz and 0.87 at 2 kHz, highlighting the distinction between random and normal incidence measurement techniques. The observed high frequency gains align with findings indicating that lignocellulosic composites exhibit efficient absorption above 1 kHz, attributed to their fine pore networks, when compared to other natural fiber systems [4, 13, 29, 33].

#### IV. DISCUSSION

The results of this study demonstrate a significant enhancement in the SAC of the sugarcane bagasse-based composite panels with the introduction of partial perforations. The samples with perforations, particularly those with a 1 mm diameter and 75% perforation depth, exhibited SAC values reaching 0.98 at frequencies between 1500 Hz and 1600 Hz, which is indicative of near-perfect sound absorption (Figure 7(a)). These findings support those in [23, 28], where it was shown that perforated panels can improve sound absorption by providing additional pathways for sound energy dissipation through viscous damping and thermal conversion.

The optimal perforation depth of 75% was found to significantly improve SAC, especially at mid and high frequencies (1000 Hz–1600 Hz), consistent with research suggesting that deeper perforations allow for better sound wave penetration and energy dissipation within porous materials [12, 22]. In comparison, the non-perforated (flat) samples demonstrated considerably lower SAC values, ranging from 0.03 to 0.44, especially at low to mid frequency. This aligns with the general trend that non-perforated materials are less effective at absorbing sound compared to their perforated counterparts [31]. Therefore, the introduction of perforations, particularly with the optimal diameter and depth, clearly enhances the acoustic performance of bagasse-based composites, confirming the potential of partial perforation designs to optimize sound absorption.

The enhanced SAC observed in the perforated composites can be attributed to the mechanisms of absorption in porous materials, which involve viscous losses, thermal conduction, and inertial effects [35]. When sound waves interact with the perforated surface, they generate a shear force between the air molecules and the fiber structure, leading to energy dissipation through friction and conversion of sound energy into heat. This phenomenon, known as viscous damping, is particularly effective at higher frequencies, where the sound wave's shorter wavelength allows for more efficient interaction with the material [32].

Moreover, the increased porosity from the perforations facilitates better air movement within the material, enhancing the efficiency of the viscous damping mechanism [32]. The interaction between the sound waves and the porous network in the composite leads to greater attenuation of sound energy, thus

improving the material's ability to absorb sound. These findings are consistent with those in [6, 7], which highlight the crucial role of porosity, pore distribution, and fiber alignment in optimizing sound absorption performance.

The results of this study indicate that the perforation diameter plays a significant role in the sound absorption properties of the composites. The 1 mm perforations consistently outperformed the 2 mm and 3 mm perforations in terms of SAC, especially at mid to high frequencies (Figure 7(a)). This can be explained by the relationship between the perforation size and pore interconnectivity. Smaller perforations, such as those with a diameter of 1 mm, enhance the interaction between the sound waves and the material by increasing the connectivity of the internal pores, thus promoting greater energy dissipation [23].

As the perforation diameter increased to 2 mm and 3 mm, the SAC decreased, particularly at lower frequencies, as the larger perforations reduced the effectiveness of sound wave penetration into the material. This observation is in line with [30, 31], where it is stated that too large perforations may reduce the material's ability to trap sound waves, resulting in diminished acoustic performance. Therefore, optimizing the perforation size is crucial in achieving high SAC values, particularly at mid and high frequencies.

A key finding in this study is the frequency-specific performance of the sugarcane bagasse composites. As shown in the results, the composites performed well at mid to high frequencies, with peak SAC values of 0.98 at 1500 Hz and 1600 Hz for samples with 1 mm perforations and 75% depth (Figure 7(a)). However, at lower frequencies (200 Hz–600 Hz), the SAC was significantly lower, ranging from 0.03 to 0.1. This is consistent with [32, 33, 36], where it was noted that natural fiber composites generally exhibit better sound absorption at higher frequencies due to their smaller pore structures and more efficient interaction with sound waves.

The reduced SAC at lower frequencies can be attributed to the longer wavelength of low-frequency sound waves, which are less likely to interact effectively with the smaller pores of the material. This is a common limitation observed in many bio-based composites, including those made from sugarcane bagasse [34]. To enhance low-frequency absorption, modifications, such as increasing panel thickness or optimizing pore structure, were proposed in [32, 37]. Future research may explore these modifications to further improve the acoustic performance of these materials.

Another significant observation from the results is the impact of the perforation size on the effective surface area available for sound absorption. While larger perforations allow for greater airflow through the material, they may also reduce the internal pore connectivity, leading to lower SAC values. For example, the 3 mm perforations exhibited the lowest SAC values, particularly at lower frequencies, as larger holes disrupted the material's ability to trap and dissipate sound energy [38, 39].

This observation supports the findings of [23, 31], where it was stated that small to medium-sized perforations are more effective in improving sound absorption by enhancing energy

loss mechanisms such as viscous damping and thermal conduction. Excessively large perforations can lead to a loss of structural integrity, making the material less effective in absorbing sound, particularly at lower frequencies.

While this study provides valuable insights into the acoustic performance of sugarcane bagasse-based composites with partial perforations, there are several limitations that need to be addressed in future research. First, the study focused on a narrow frequency range (200 Hz–1600 Hz), which may not fully capture the material's performance across a broader spectrum of sound frequencies. To improve the generalizability of the results, future studies should extend the frequency range to include lower frequencies, where significant sound absorption often occurs [40]. Second, while the perforation diameter and depth were found to significantly affect the SAC, other factors, such as panel thickness, porosity ratio, and fiber orientation, also influence the material's acoustic performance. Further research should explore the combined effects of these factors and investigate the optimal configurations for enhancing sound absorption at both low and high frequencies.

Finally, the environmental and economic benefits of using sugarcane bagasse as a raw material for sound absorbers should be assessed through Lifecycle Analysis (LCA) to quantify the environmental impact of these materials compared to conventional synthetic sound absorbers. This will help validate their sustainability and feasibility for large-scale applications in noise control [41, 42].

## V. CONCLUSION

This study investigates the acoustic performance of sugarcane bagasse-based composite panels with partial perforations, focusing on the effects of the perforation diameter and depth on sound absorption. The results demonstrate that perforation significantly enhances the Sound Absorption Coefficient (SAC) of these bio-composite panels, especially at mid and high frequencies. The composite panel with 1 mm perforations and a 75% perforation depth achieved the highest SAC, nearing 0.98 at 1500 Hz and 1600 Hz, showcasing the potential of optimizing perforation patterns to improve acoustic performance.

The analysis of the perforation diameter revealed that smaller perforations (1 mm) provided better sound absorption than larger perforations (2 mm and 3 mm), particularly at higher frequencies. Additionally, the increased perforation depth was found to improve SAC, with deeper perforations allowing for more effective sound wave penetration into the material, leading to better energy dissipation.

However, the study also identified that perforations larger than 2 mm could reduce the material's overall acoustic performance, particularly at lower frequencies. This highlights the importance of balancing perforation size to optimize both structural integrity and sound absorption performance.

The current perforation strategy enhances absorption in the mid to high frequency range; however, it is less effective for frequencies below approximately 600 Hz in 30 mm panels. Future research will focus on enhancing low frequency response through the use of thicker panels, graded or dual layer

media, and hybridization with micro perforated overlays or shallow air cavities. These strategies have demonstrated the ability to shift resonance toward lower frequency bands. In addition to acoustics, assessing durability and compliance—specifically moisture uptake, friability, and fire behavior—along with process scalability, such as Computer Numerical Control (CNC) or die punching for consistent partial depth perforations, is noteworthy. A life cycle and techno-economic assessment will evaluate bagasse panels in comparison to polyurethane and mineral wool solutions.

## REFERENCES

- [1] N. Rastegar, A. Ershad-Langroudi, H. Parsimehr, and G. Moradi, "Sound-absorbing porous materials: a review on polyurethane-based foams," *Iranian Polymer Journal*, vol. 31, no. 1, pp. 83–105, Jan. 2022, <https://doi.org/10.1007/s13726-021-01006-8>.
- [2] C. Zhang *et al.*, "The review of fiber-based sound-absorbing structures," *Textile Research Journal*, vol. 93, no. 1–2, pp. 434–449, Jan. 2023, <https://doi.org/10.1177/00405175221084736>.
- [3] S. Sakthivel *et al.*, "Sound absorbing and insulating properties of natural fiber hybrid composites using sugarcane bagasse and bamboo charcoal," *Journal of Engineered Fibers and Fabrics*, vol. 16, Jan. 2021, Art. no. 15589250211044818, <https://doi.org/10.1177/15589250211044818>.
- [4] N. Gboe and R. Grubliauskas, "Advancing Sustainable Acoustic Solution: Exploring the Sound Absorption Characteristics of Biodegradable Agricultural Wastes, Coconut Fiber, Groundnut Shell, and Sugarcane Fiber," *CONNECT. International Scientific Conference of Environmental and Climate Technologies*, pp. 131–131, May 2024, <https://doi.org/10.7250/CONNECT.2024.096>.
- [5] M. P. Renandito *et al.*, "Modification of Sugarcane Bagasse Fiber: A Comparative Study of Alkali and TEMPO Treatments," *Engineering, Technology & Applied Science Research*, vol. 15, no. 3, pp. 22394–22400, June 2025, <https://doi.org/10.48084/etasr.10517>.
- [6] R. Manikandan, R. Gowrishankar, S. Nandhini, R. Avanthika, K. Shneka, and S. Kowsalya, "A Comparative Study on Acoustic Parameters of Porous Absorber of polyamide, polyester and polyurethane," *International Scientific Journal of Engineering and Management*, vol. 2, no. 5, pp. 1–19, May 2023, <https://doi.org/10.55041/ISJEM00979>.
- [7] P. Leclaire, O. Umnova, T. Dupont, and R. Panneton, "Acoustical Properties of air-saturated porous material with periodically distributed dead-end pores," *The Journal of the Acoustical Society of America*, vol. 137, no. 4, pp. 1772–1782, Apr. 2015, <https://doi.org/10.1121/1.4916712>.
- [8] S. Kuschnitz, T. P. Ring, H. Watschke, S. C. Langer, and T. Vietor, "Design and Additive Manufacturing of Porous Sound Absorbers—A Machine-Learning Approach," *Materials*, vol. 14, no. 7, Apr. 2021, Art. no. 1747, <https://doi.org/10.3390/ma14071747>.
- [9] K. Attenborough, "Microstructures for lowering the quarter wavelength resonance frequency of a hard-backed rigid-porous layer," *Applied Acoustics*, vol. 130, pp. 188–194, Jan. 2018, <https://doi.org/10.1016/j.apacoust.2017.09.022>.
- [10] K. Ram and P. K. Bajpai, "Performance analysis of hybrid bio-composites developed through different processing routes for automobile application," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 237, no. 20, pp. 4769–4780, Oct. 2023, <https://doi.org/10.1177/09544062231156514>.
- [11] P. Barman, P. P. Dutta, M. Bardalai, and P. P. Dutta, "Experimental investigation on bamboo fiber reinforced epoxy polymer composite materials developed through two different techniques," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 238, no. 6, pp. 2185–2204, Mar. 2024, <https://doi.org/10.1177/09544062231195474>.
- [12] J. M. C. Puguan, A. G. M. Pornea, J. L. A. Ruello, and H. Kim, "Double-Porous PET Waste-Derived Nanofibrous Aerogel for Effective Broadband Acoustic Absorption and Transmission," *ACS Applied*

- Polymer Materials*, vol. 4, no. 4, pp. 2626–2635, Apr. 2022, <https://doi.org/10.1021/acsapm.1c01918>.
- [13] A. Putra, Y. Abdullah, H. Efendy, W. M. F. W. Mohamad, and N. L. Salleh, "Biomass from Paddy Waste Fibers as Sustainable Acoustic Material," *Advances in Acoustics and Vibration*, vol. 2013, no. 1, 2013, Art. no. 605932, <https://doi.org/10.1155/2013/605932>.
- [14] T. Hassan *et al.*, "Factors Affecting Acoustic Properties of Natural-Fiber-Based Materials and Composites: A Review," *Textiles*, vol. 1, no. 1, pp. 55–85, 2021, <https://doi.org/10.3390/textiles1010005>.
- [15] N. N. A. N. Pa, M. H. W. Ibrahim, A. H. A. Ghani, A. Z. M. Ali, and M. F. Arshad, "Compressive Strength of Construction Materials Containing Agricultural Crop Wastes: A Review," *MATEC Web of Conferences*, vol. 103, 2017, Art. no. 01018, <https://doi.org/10.1051/mateconf/201710301018>.
- [16] R. Mandala, G. Hegde, D. Kodali, and V. R. Kode, "From Waste to Strength: Unveiling the Mechanical Properties of Peanut-Shell-Based Polymer Composites," *Journal of Composites Science*, vol. 7, no. 8, Aug. 2023, Art. no. 307, <https://doi.org/10.3390/jcs7080307>.
- [17] S. Rane and D. S. Thakker, "Development of Sustainable tableware from waste," *ScienceOpen Preprints*, May 2023, <https://doi.org/10.14293/PR2199.000115.v1>.
- [18] C. Rubino *et al.*, "Composite Eco-Friendly Sound Absorbing Materials Made of Recycled Textile Waste and Biopolymers," *Materials*, vol. 12, no. 23, Jan. 2019, Art. no. 4020, <https://doi.org/10.3390/ma12234020>.
- [19] Y. Duan, L. Zhang, H. Su, D. Yang, and J. Xu, "Eco-Innovation: Corn Stover as the Biomaterial in Packaging Designs," *Sustainability*, vol. 16, no. 4, 2024, Art. no. 1381, <https://doi.org/10.3390/su16041381>.
- [20] S. Suckley, P. Deenuch, N. Disjareon, and S. Phongtamrug, "Effects of Alkali Treatment and Fiber Content on the Properties of Bagasse Fiber-Reinforced Epoxy Composites," *Key Engineering Materials*, vol. 757, pp. 40–45, Oct. 2017, <https://doi.org/10.4028/www.scientific.net/KEM.757.40>.
- [21] T. A. Nguyen *et al.*, "Enhancing epoxy composite materials through lime-treated sugarcane bagasse and glass fiber reinforcement: Morphological, mechanical, and flame-retardant insights," *Vietnam Journal of Chemistry*, vol. 63, no. 1, pp. 68–80, 2025, <https://doi.org/10.1002/vjch.202400059>.
- [22] I. Prasetyo, J. Sarwono, and I. Sihar, "Study on inhomogeneous perforation thick micro-perforated panel sound absorbers," *Journal of Mechanical Engineering and Science*, vol. 10, no. 3, pp. 2289–4659, Dec. 2016, <https://doi.org/10.15282/jmes.10.3.2016.12.0218>.
- [23] V. Sekar *et al.*, "Effect of Perforation Volume on Acoustic Absorption of the 3D Printed Micro-Perforated Panels made of Poly(lactic Acid reinforced with Wood Fibers)," *Journal of Physics: Conference Series*, vol. 2120, 2021, Art. no. 012039, <https://doi.org/10.1088/1742-6596/2120/1/012039>.
- [24] *Standard Test Method for Impedance and Absorption of Acoustical Materials Using a Tube, Two Microphones, and a Digital Frequency Analysis System*, ASTM E1050-98, ASTM International, 2006
- [25] E. Jayamani, S. Hamdan, and N. B. Suid, "Experimental Determination of Sound Absorption Coefficients of Four Types of Malaysian Wood," *Applied Mechanics and Materials*, vol. 315, pp. 577–581, 2013, <https://doi.org/10.4028/www.scientific.net/AMM.315.577>.
- [26] *Impedance/Transmission Loss Tube Kit Types 4206, 4206-A, 4206-T - User Manual*, Hottinger Brüel & Kjær, 2021. [Online]. Available: <https://media.hbkworld.com/m/0e4938933a372f21/original/-Impedance-Transmission-Loss-Measurement-Tubes-Types-4206-4206-A-4206-T.pdf>.
- [27] J. M. C. Puguan, D. B. A. Agbayani, A. J. V. Sadural, and H. Kim, "Enhanced Low Frequency Sound Absorption of Bilayer Nanocomposite Acoustic Absorber Laminated with Microperforated Nanofiber Felt," *ACS Applied Polymer Materials*, vol. 5, no. 11, pp. 8880–8889, 2023, <https://doi.org/10.1021/acsapm.3c01249>.
- [28] B. Song, L. Peng, F. Fu, M. Liu, and H. Zhang, "Experimental and Theoretical Analysis of Sound Absorption Properties of Finely Perforated Wooden Panels," *Materials*, vol. 9, no. 11, Nov. 2016, Art. no. 942, <https://doi.org/10.3390/ma9110942>.
- [29] M. Mohammadi, M. R. Ishak, M. T. H. Sultan, and E. S. Zainudin, "A Comprehensive Review of Factors Influencing the Sound Absorption Properties of Micro-Perforated Panel Structures," *Journal of Vibration Engineering & Technologies*, vol. 13, May 2025, Art. no. 319, <https://doi.org/10.1007/s42417-025-01849-y>.
- [30] D. J. Larner and J. L. Davy, "Predicting the absorption of perforated panels backed by resistive textiles," *Noise Control Engineering Journal*, vol. 64, no. 2, pp. 259–267, Mar. 2016, <https://doi.org/10.3397/1/376376>.
- [31] B. T. Samuel, M. Barburski, E. Witezak, and A. K. Puszkarcz, "Enhancement of low and medium frequency sound absorption using fabrics and air gaps," *Textile Research Journal*, vol. 93, no. 21–22, pp. 5112–5123, 2023, <https://doi.org/10.1177/00405175231186176>.
- [32] L. Shen, Y. Luo, L. Ni, M. Liang, S. Zhou, and H. Zou, "Improved Sound Absorption Performance of Melamine/Waterborne Polyurethane Composite Foams Using Cyclic Freeze–Thawing," *ACS Applied Polymer Materials*, vol. 6, no. 6, pp. 3564–3571, Mar. 2024, <https://doi.org/10.1021/acsapm.3c03125>.
- [33] X. Liu, X. Yan, and H. Zhang, "Effects of pore structure on sound absorption of kapok-based fiber nonwoven fabrics at low frequency," *Textile Research Journal*, vol. 86, no. 7, pp. 755–764, 2015, <https://doi.org/10.1177/0040517515599742>.
- [34] C. He *et al.*, "Enhanced Sound Absorption Properties of Ceramics with Graphene Oxide Composites," *ACS Omega*, vol. 6, no. 50, pp. 34242–34249, Dec. 2021, <https://doi.org/10.1021/acsomega.1c03362>.
- [35] X. Ren *et al.*, "Formation of Interpenetrating-Phase Composites Based on the Combined Effects of Open-Cell PIF and Porous TPU Microstructures for Enhanced Mechanical and Acoustical Characteristics," *ACS Applied Polymer Materials*, vol. 5, no. 10, pp. 8023–8032, 2023, <https://doi.org/10.1021/acsapm.3c01264>.
- [36] Z. Daecipour, V. Safdari, and A. Nurbakhsh, "Evaluation of the Acoustic Properties of Wood-Plastic-Chalk Composites," *Engineering, Technology & Applied Science Research*, vol. 7, no. 2, pp. 1540–1545, Apr. 2017, <https://doi.org/10.48084/etasr.830>.
- [37] Y. Hou *et al.*, "Ultralight biomass-derived carbon fibre aerogels for electromagnetic and acoustic noise mitigation," *Journal of Materials Chemistry A*, vol. 10, no. 42, pp. 22771–22780, 2022, <https://doi.org/10.1039/D2TA06402B>.
- [38] Z. R. Z. Zulkarnain, M. J. M. Nor, and S. Abdullah, "Perforated Plate Backing with Coconut Fiber as Sound Absorber for Low and Mid Range Frequencies," *Key Engineering Materials*, vol. 462–463, pp. 1284–1289, 2011, <https://doi.org/10.4028/www.scientific.net/KEM.462-463.1284>.
- [39] M. Carlesso *et al.*, "Near-Net-Shaped Porous Ceramics for Potential Sound Absorption Applications at High Temperatures," *Journal of the American Ceramic Society*, vol. 96, no. 3, pp. 710–718, 2013, <https://doi.org/10.1111/jace.12160>.
- [40] S. Charyyev *et al.*, "Optimization of hexagonal-pattern minibeam for spatially fractionated radiotherapy using proton beam scanning," *Medical Physics*, vol. 47, no. 8, pp. 3485–3495, 2020, <https://doi.org/10.1002/mp.14192>.
- [41] I. O. Adejumo, O. A. Adebiyi, I. O. Adejumo, and O. A. Adebiyi, "Agricultural Solid Wastes: Causes, Effects, and Effective Management," in *Strategies of Sustainable Solid Waste Management*, IntechOpen, 2021.
- [42] S. Seetharaman, J. Subramanian, R. A. Singh, W. L. E. Wong, M. L. S. Nai, and M. Gupta, "Mechanical Properties of Sustainable Metal Matrix Composites: A Review on the Role of Green Reinforcements and Processing Methods," *Technologies*, vol. 10, no. 1, Feb. 2022, Art. no. 32, <https://doi.org/10.3390/technologies10010032>.