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Reducing Vehicle Heating, Ventilation and Air Conditioning Noise Using Low-Cost and Biodegradable Natural Materials from Coconut Fiber Absorber

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Abstract. The heating, ventilation, and air conditioning (HVAC) units in vehicles can produce significant noise, lowering the sound quality inside the vehicle and reducing passenger comfort. While noise control methods are available, they can be expensive and harmful to the environment. To address these issues, this study aims to investigate using low-cost and biodegradable natural materials, specifically coconut fibers, for vehicle HVAC noise control. The study utilized coconut fibers, which have sound absorption properties reaching 42 dBA, to treat an actual Perodua HVAC unit. The treatment targeted the HVAC noise spectrum at low, medium, and high blower speeds, resulting in reduced Sound Pressure Levels (SPL) at the passenger's ear position. The composite was applied to the air inlet head and inlet channel of the HVAC system using a specific combination of coconut fiber content. The research identified the sources of noise in the highest contributions that occurred at the blower fan unit and treated the required areas. In terms of numerical data, the results showed that the treatment significantly reduced the noise level by 11 dBA. Additionally, the experiment found that the 8% fiber ratio at low speed decreased by 14.28% following the treatment. Similarly, the fiber ratio at medium and high speeds saw reductions of 15.47% and 17.56%, respectively. This study presents a promising solution for reducing noise in vehicle HVAC units using cost-effective and eco-friendly materials. Future research should focus on optimizing coconut fiber ratios, evaluating long-term durability and biodegradability, validating real-world applicability, and establishing standardized testing protocols to improve and confirm the effectiveness of coconut fiber-based noise control in automotive HVAC systems.

Keywords: Biodegradable materials; Coconut fibers; HVAC noise control; Natural fiber absorber; Noise reduction; Vehicle acoustic comfort

1. Introduction

A vehicle's interior sound quality is crucial and requires attention to Noise, Vibration, and Harshness (NVH). The reduction of noise inside a car improves passenger comfort and driving experience and reduces distraction. Enhanced sound quality also influences customer perception of the automotive product, making the vehicle more attractive and

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competitive (Jennings *et al.,* 2010). Advancements in research and development over the past two decades have revolutionized vehicle engines, making them quieter and delivering superior sound. This progress has resulted in increased perceptibility of secondary sound sources within the vehicle cabin, such as heating, ventilation and air-conditioning (HVAC) systems, entertainment systems, and audio driver assist systems. Among these sources, the HVAC system stands out as the most dominant noise source in the vehicle's interior space, operating continuously while the vehicle is in motion (Singh and Mohanty, 2018). It is fascinating to observe the increasing attention given to the study and reduction of aeroacoustics noise generated by automotive Heating, Ventilation, and Air Conditioning (HVAC) systems, particularly in electric vehicles where other sources of noise are comparatively less significant (Fei and Wang, 2023; Hariharan *et al.,* 2022). Improving acoustic comfort is crucial, and this involves reducing noise from the ventilation system, as well as addressing wind noise and other noise sources (Sun *et al.,* 2024a; Zhou *et al.,* 2023; Taheri, Hosseini, and Razban, 2022; Back *et al.,* 2021). The HVAC noise is classified into low-frequency and high-frequency components, which helps to understand the sources and characteristics of the noise. Humming and buzzing sounds are typically associated with low-frequency noise emanating from components such as blowers and condensers. Notably, these noises may not be as perceptually irritating as high-frequency tonal noises, but they still play a significant role in overall cabin noise (Yoon *et al.,* 2020).

Passengers can be particularly disturbed by tonal noises at high frequencies. These noises can come from air outlets, channels, and system discontinuities such as junctions. These stand out against background noise and can make it seem like the overall noise level has increased, leading to discomfort (Zhou *et al.,* 2023). It is essential to reduce both low-frequency and high-frequency noise components in automotive HVAC systems to achieve premium acoustic comfort for vehicle occupants. This may involve redesigning components to minimize vibration and turbulence, optimizing airflow paths to reduce turbulence and pressure fluctuations, and using sound-absorbing materials or baffles to dampen noise propagation.

For optimal performance, HVAC units have a blower that generates noise (Amer, 2024; Hasegawa and Sakaue, 2024; Sun *et al.,* 2024b; Li *et al.,* 2024; Fei and Wang, 2023; Gowree *et al.,* 2023; Qingyi *et al.,* 2023). To reduce this noise, conventional strategies involve designing changes to the blower and its blades (Sun, Xu, and Shi, 2021; Smith, Filippone, and Bojdo, 2020; Han *et al.,* 2019; Jiang *et al.,* 2019). While design changes can reduce this noise, it needs to focus on post-production noise control strategies for existing units (Yang, Wang, and Wang, 2023; Pulvirenti, Totaro, and Parizet, 2023; Loreto *et al.,* 2020). Two methods for post-production noise control are active and passive noise control. Passive noise control is more cost-effective and works best at frequencies above 500 Hz, providing noise reduction throughout the interior space. For example, synthetic sound-absorbing materials such as micro-perforates, fiberglass, glass wool, and polypropylene can achieve up to 6-10 dB noise reduction (Mohammadi *et al.,* 2024; Tao *et al.,* 2021). However, these materials were expensive and had a high carbon footprint. Additionally, they are not biodegradable or recyclable, making them an unsustainable choice. Although active noise control can be effective, it is expensive and only works in specific areas of the vehicle's interior space. To minimize noise pollution and promote sustainability, the method should prioritize passive noise control using environmentally friendly materials.

The airflow powered by machines often generates noise due to the air flowing around them, especially in low-mach-number flows. Flow-induced noise reduction strategies typically fall into two categories: active control and passive control (Shige *et al.,* 2024). Several studies have adopted the passive control approach to reduce flow-induced noise.

This method entails replacing specific parts of the object, which are exposed to fluid flow, with porous material. By doing so, the noise is significantly reduced without altering the shape of the object. Notably, the automotive industry shifted towards Natural Fiber (NR) materials for noise control since they are sustainable, cost-effective, and effective. Materials like jute, cotton, flax, kenaf, hemp, coconut coir, bamboo curls, and bananas are excellent sound absorbers, affordable, lightweight, and environmentally friendly (Bisheh, 2024; Nawawithan *et al.,* 2024; Singh *et al.,* 2024; 2023; Dattatreya *et al.,* 2023; Sahib-dua *et al.,* 2023; Patel, Mishra, and Choudhary, 2022; Hariprasad *et al.,* 2020; Hadiji *et al.,* 2020). NRs are also versatile and can be molded into various shapes, making them a flexible option for different components. Using NR materials, manufacturers can achieve effective noise control while reducing production costs and meeting sustainability goals. Moreover, this trend reflects broader industry efforts towards eco-friendly and cost-efficient solutions in automotive design and manufacturing. According to Mago *et al.* (2022), Rubber-Bamboo Biochar (BB) composite has been proven to be the most effective natural material for sound absorption. They used NR to treat a sound absorber in an automotive unit, and the Sound Transmission Loss (STL) was significantly increased by 8% and 11% compared to NR composites upon adding 10 and 20 per hundred rubber of BB, respectively. Recent studies have proven that NR/polymer composites reinforced with porous fabric exhibit excellent sound energy absorption properties. Notably, the hollow conjugated cross-section provides the maximum noise absorption. Nonwoven fabrics composed of biodegradable and recyclable jute caddies and flax comber noil also have significant noise absorption properties despite being inexpensive. In addition, a higher punch density results in better compactness of nonwoven fabric, which leads to improved sound absorption properties. Meanwhile, layered nonwoven structures are responsible for better sound absorption properties due to the presence of an air layer (Paul, Ahirwar, and Behera, 2022).

Nearly all NRs play a crucial role in absorbing unwanted sound. NR sound absorbers are available in the form of raw materials, fiber assemblies, and composites. The study of absorption materials is crucial to understanding the relationship between material and sound absorption coefficient, as well as overall performance. Properly designed materials can optimize the prevention of noise from the source and enhance STL. Moreover, various studies have proposed optimization strategies for noise control in material design. Firstly, material designs are characterized through measurement testing and analyzed for sound transmission characteristics of the composite using experiments (Zulkarnain *et al.,* 2024; Choudhary *et al.,* 2023; Ciach *et al.,* 2022; Abdi *et al.,* 2021; Bhingare and Prakash 2021; Yang, *et al.,* 2020; Da-Silva *et al.,* 2019). Secondly, numerical studies, such as Finite Element Analysis (FEA), are utilized to optimize and validate the transmission loss and vibration through composite materials (Lim, Yaw, and Chen, 2022; Araújo and Madeira, 2020; Soltani *et al.,* 2020). These studies indicate that optimized design can significantly mitigate the spread of noise contaminants and enhance acoustical contributions. Several studies have suggested that NR sound absorbers offer many advantages over conventional absorbers. However, not all NRs have the necessary properties to replace mineral fiber and glass fiber. Therefore, it is crucial to compare the sound absorption properties of NRs and conventional absorbers. To compare the differences among the absorbers, the sound absorption curves presented by the previous researcher (Yang *et al.,* 2020) have been separately displayed in the absorption coefficient results. Thicker absorbers made of coir fiber exhibit better sound absorption properties than thinner absorbers, such as Yucca Gloriosa fiber. Moreover, coir fiber demonstrates good absorption agreement with a coefficient of around 0.95 in the frequency range of 63-6,300 Hz. Thicker absorbers made of coir fiber with a loose fiber structure demonstrate worse sound absorption compared to thinner absorbers.

Accordingly, most natural absorbers demonstrate better sound absorption than glass fiber. The utilization of natural resources in composite production offers a more environmentally friendly approach to pollution reduction. The effectiveness of bamboo biochar as a filler in natural rubber composites for vibration and noise control has been investigated by Mago *et al.* (2022) and Khair *et al.* (2015). Materials like rubber (Corredor -Bedoya, Zoppi, and Serpa, 2017), wool (Ilangovan *et al.*, 2022), single layer micro-perforated panel (Esraa *et al.*, 2022), Sludge and Fly Ash (Hiadayani *et al.*, 2023), and silica (Yusoff *et al.*, 2023) are commonly used to absorb vibrations and noise pollution in engineering applications. Natural fibers are favored due to their eco-friendly nature, competitive mechanical performance, and renewable availability throughout the year.

Furthermore, advanced computational simulation testing methodologies can help identify noise sources and evaluate the effectiveness of noise reduction measures. This can facilitate the development of quieter HVAC systems for automotive applications. The previous researcher approached reducing noise in commercial electric vehicle HVAC systems. A multifaceted set of wind tunnel numerical simulations and practical applications demonstrated significant reductions of over 20 dB in their design. Researchers studied the noise generation of air outlets in a car's HVAC system. They simulated the flow and acoustic perturbations using a hybrid aeroacoustics simulation and also experimented to observe the interaction between the throttle valve and fins (Ravichandran *et al.*, 2024). In addition, numerical analysis has been successfully used to analyze the noise emitted by automobiles (Zhang *et al.*, 2022), especially the noise generated by the exhaust system, which significantly impacts human health. To improve this situation, CFD analysis was conducted on the existing muffler and three newly designed mufflers, considering the inlet velocity. The results indicated that increasing the pressure drop (improving aerodynamic performance) also reduced noise pollution (Kalita and Singh, 2022).

Extensive research has been conducted in aeronautical engineering and high-speed flows to explore the reduction of flow-induced noise using NR materials. This innovative study utilizes coconut NR materials that offer exceptional acoustic transparency and minimal fluid permeability to effectively reduce noise in a relatively low-speed flow field. By minimizing fluid resistance, conventional coconut fiber materials may not affect the drag force and velocity fluctuations near their surface; the materials are designed to alleviate this issue. Therefore, the recirculation inlet should be treated by installing acoustic linings inside the ductwork and smooth surface finishes to avoid drag force. Thus, by utilizing coconut fiber materials, this research aims to effectively minimize noise emanating from the blower motor. The study delves into the potential of these innovative materials in mitigating flow-induced noise in Malaysian vehicle (Perodua Viva) HVAC systems. This study is unique since it investigates using inexpensive and environmentally friendly coconut fibers as a natural material to absorb noise from HVAC systems in vehicles, notably the Perodua Viva. Prior studies have primarily examined synthetic and other NRs. However, using coconut fibers presents an environmentally friendly and economically efficient approach to tackle low-frequency and high-frequency noise elements. This study successfully reduces noise in car HVAC systems by focusing on the noise sources near the blower motor and adjusting the fiber ratio at various speeds. The result is an 11 dBA decrease in noise, offering a viable and environmentally friendly solution to improve acoustic comfort.

2. Methods

The methodology used to perform numerical evaluations and experimental noise control methods involved four main steps, as depicted in Appendix 1. First, an impedance tube was used to evaluate the coconut composite's sound absorption and transmission loss, and raw data was collected to characterize the composite's properties in noise absorption capabilities. In the second step, the main contribution of noise produced by the vehicle's HVAC system was evaluated, followed by a numerical method to analyze the appropriate treatment to be implemented in the HVAC system. Finally, the coconut composite treatment in the HVAC system was analyzed experimentally in the last step.

2.1. Description of the HVAC unit

The HVAC unit being studied was a Malaysian vehicle produced by Perodua. It has an 850 cc engine and is made of plastic. The unit consists of several key components, including a fresh air inlet, recirculation inlet, and outlet vents, as illustrated in Appendix 2. The observation focuses on higher noise levels produced by the HVAC system based on measurements, and several factors could contribute to this phenomenon. This includes blower speed, air flow restriction, vibration, and restriction. The air enters the unit through the recirculation inlet vent (number 1), passes through the blower, and then flows over the evaporator.

2.2. *Coconut fiber extraction process*

The process of extracting coconut fiber from the inner flesh of coconuts involves peeling, shredding, cleaning, and sun-drying. To reveal the inner flesh, a machete is used to peel the outer skin of coconuts. Consequently, the shredding breaks down the fibrous material into smaller strands, making it easier to process. The shredded coconut fiber is then cleansed with distilled water to remove any impurities and sun-dried to remove excess moisture. The physical coir fiber is generally short, ranging from 15 to 18 cm, with a diameter varying from 0.1 to 0.5 mm.

2.3. Coconut coir fiber treatment

The alkali treatment process for coconut fiber enhances its flexibility and purity. The process involves soaking the fiber in a 2% NaOH solution to break down impurities, as displayed in Appendix 3. After rinsing, the fiber is neutralized and dried to remove excess moisture. The completely treated fiber is then oven-dried to ensure its purity and readiness. This treatment process produces high-quality coconut fiber that is suitable for various applications. By following these steps, manufacturers can produce coconut fiber that meets industry standards.

2.4. Mixing Process

In the composite manufacturing process described, a mixture of polyester and hardener is combined with coconut fiber at different weight ratios to create composite samples with varying properties. The following outlines the measurement and mixing procedure for the polyester and hardener, as per the provided specifications:

Polyester Measurement: Each composite sample is measured with a total of 350 g of polyester. This specific amount serves as the base material for the composite and plays a crucial role in determining its overall composition and characteristics. The Polyester used in this study was Unsaturated polyester resin (UPR), with key ingredients such as phthalic anhydride, isophthalic acid, maleic anhydride, styrene monomer, and glycols supplied by LEZO, China.

Hardener Measurement: The hardener is added to the polyester at a specific weight ratio to initiate the curing process and ensure proper adhesion between the polyester and coconut fiber. According to Table 1, a hardener ratio of 4% is used for the ideal mixture. Mixture Preparation: The polyester and hardener are thoroughly mixed to ensure uniform distribution and proper activation of the curing process. To ensure optimal composite performance, care must be taken to achieve a consistent blend of polyester and hardener.

Table 1 Mixture of filler content in composite

Polyester (g)	Hardener (g)	Fiber (g)	Total Weight (g)	Fiber Weight (%)	Hardener (%)
336	14	0	350	0	4
329.28	13.72	7	350	2	4
322.56	13.44	14	350	4	4
315.84	13.16	21	350	6	4
309.12	12.88	28	350	8	4

Coconut Fiber Addition: Once the polyester and hardener mixture is prepared, coconut fiber is added to achieve the desired weight ratio specified for each composite sample. This step involves combining the polyester-hardener mixture with the specified amount of coconut fiber and thoroughly mixing them to ensure proper fiber impregnation.

Composite Sample Preparation: After mixing the polyester, hardener, and coconut fiber, the composite mixture is molded or cast into the desired shape or form and allowed to cure according to the manufacturer's instructions. This results in the formation of composite samples with varying fiber content and properties suitable for testing and evaluation.

By following these steps and carefully controlling the ratios of polyester, hardener, and coconut fiber, researchers can produce composite samples with predictable and consistent properties, allowing for accurate analysis and comparison of different formulations.

Mixing Polyester and Hardener: The polyester and hardener mixture, as displayed in Appendix 4, is prepared. This mixture is carefully blended to ensure proper curing process activation and achieve the desired properties in the composite material. Pouring Polyester-Hardener Mixture: With the coconut fiber in place within the mold, the polyester-hardener mixture is slowly poured into the mold. The pouring process is conducted in a controlled manner to ensure even coverage and distribution of the mixture over the entire bottom area of the mold. This ensures a smooth and flawless finish through the lay-up technique.: As the polyester-hardener mixture fills the mold, attention is paid to achieving a smooth and flawless surface finish to the fiber stacking. This may involve using tools or techniques to spread the mixture evenly and eliminate any air bubbles or irregularities. Curing Process: Once the mold is filled with the polyester-hardener mixture, the composite material is allowed to cure. The curing process initiates the chemical reaction between the polyester and hardener, forming a solid and durable composite product.

2.5. Material Testing

The ACUPRO Version 4.5 impedance tube was utilized to measure the acoustic properties of materials and systems according to ISO 10534-1 (ISO, 2002) and ASTM E2611 standards for transmission loss measurement. The ACUPRO tube is made of stainless steel and has an internal diameter of 38 mm, and it is equipped with supports and leveling screws. The operating frequency range level was from 50 Hz to 5,000 Hz, and four microphones were used for measurement. The impedance tube was employed to measure both the sound absorption coefficient and the transmission loss across the specified frequency ranges. This is where the sound absorption coefficient determines the amount of sound energy absorbed by a material and provides insights into the material's ability to absorb sound. Transmission loss, on the other hand, evaluates the reduction in sound energy as it passes through a material or system, indicating the effectiveness of the material or system in blocking sound transmission. Appendix 5 displays samples testing of 38 mm in diameter that were prepared for both the sound absorption coefficient and transmission loss testing.

2.6. Noise evaluation of the baseline HVAC unit

The binaural sounds measured at each point have the possibility of noise produced by digital sound level meter AS804 to analyze sound quality. Correspondingly, we obtain the Sound Pressure Levels (SPL) with decibel (dB) units in a range of 30 to 130 dB (±1.5 dB). Appendix 6 illustrates the equipment used for detecting and measuring the noise evaluation of the HVAC system. In this context, an anemometer is utilized to measure the airflow speed, providing results within the range of 0 m/s - 30 m/s (±1 m/s). The temperature is measured in degrees Celsius (°C) within a range of 0 – 50 (±0.5°C).

The process of selecting appropriate measurement sites within an HVAC system requires several steps to ensure precise and representative data collection. Here is a step-by-step guide on how it can be performed: 1. Identify specific locations within the HVAC system where measurements need to be taken. 2. Select evaluation points providing representative information about the system's efficiency. 3. Properly position and calibrate the experimental equipment. 4. Start the vehicle's engine and turn on the air conditioning system. 5. Conduct measurements of airflow, temperature, and other relevant parameters at each designated measurement point. 6. Analyze the collected data to evaluate the HVAC system's performance and identify improvement areas.

Decibel (dB) measurements and frequency ranges were collected in the HVAC system, revealing that the highest A-weighted (dBA) values occurred closest to the fresh air inlet, denoted as number 1 in Appendix 2. This is due to the proximity to the blower (speed motor) and airflow restriction. Appendix 7 illustrates the recorded noise level data using a mini sound meter to evaluate the noise in the recirculation inlet section on maximum power. The measurements were obtained in a silent environment to ensure precise readings of noise levels. Additionally, noise, flow, and temperature were recorded from all air outlet valves in the cabin, with 10 s readings for each. Based on the speed motor specification, it was given at 1,500 rpm and 5 kg of mass and produced 25 Hz of frequency for top-speed running. This critical data enables precise analysis of noise sources generated by HVAC ductwork. Additionally, it is essential for conducting numerical analysis during noise spectrum measurement.

2.7. Numerical Analysis

The numerical method used in designing the HVAC system considered the documented loudness data and SPL distribution closest to the source. ANSYS, a FEA tool, was used to analyze the composite and help with the actual design, to reduce the SPL power. At the same time, the acoustic solver in ANSYS used the natural frequencies and mode shapes of the structure for simulation. Modal analysis was employed as a linear dynamics analysis technique as presented in Equation (1). To solve the dynamic response of the structure, the equation of motion was used, where acceleration, velocity, and displacement for all points over the structure were the unknowns:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{f(t)\} \tag{1}$$

where M, $\ddot{u}$, C, $\dot{u}$, K, u, and f were denoted as mass, acceleration, damping velocity, stiffness, displacement, and load, respectively.

While for harmonic motion, the oscillation of a simple spring-mass system, the ANSYS is using Equation (2). It is a periodic motion, which can be described by an amplitude, frequency, and phase angle:

$$x = Asin(\omega t + \theta) \tag{2}$$

where A, ω and θ were denoted by amplitude, angular frequency, and phase angle.

2.8. Computational domain and details

The computational domain includes the fresh air inlet head and inlet channel. The motor was placed at the inlet channel, which is the noise source. The dimensions of the fresh air inlet can be observed in Appendix 8(A), while the computational domain size is 20 cm x 20 cm x 20 cm, as illustrated in Appendix 8(B). Appendix 8(C) presents an observation on reducing noise using coconut fiber composite.

2.9. Boundary Condition

To accurately simulate acoustic pressure, a constant frequency of 25 Hz was set at the inlet channel boundary, perpendicular to the flow direction. The noise frequency often matches the frequency of the structure's vibration and is transmitted through the air or other media. It is crucial to consider each material's specific conditions, considering its density. Hence, an acoustic region and a radiation boundary were set at the outer boundaries of the domain to ensure an impeccable simulation. It must be included in the geometry to incorporate material composite for noise treatment. Note that a solid physical interface was introduced to separate the air as the domain and the object dimension. At the same time, the sound source was presented using a mass source, and the model was ready to start the simulation process. Accordingly, this approach enhances the accuracy of our acoustic simulations and ensures the best results.

2.10. Noise Control Experimental

The final stage of the methodology involves treating the HVAC unit by lining the recirculation inlet or air flow paths with coconut composite and filling the cavities inside the ductwork near the blower intake. The detailed treatment is described in Appendix 8(C), which illustrates the recirculation inlet being covered by coconut composite. Meanwhile, a varied ratio of coconut composite effects is observed in airflow and noise absorption analysis.

3. Results and Discussion

The alkaline treatment enhances the coconut fibers for composite applications by cleaning their surfaces, increasing roughness, and modifying the material. In addition, this process degrades lignin and hemicellulose, theirby improving the mechanical properties. Coconut fibers are successfully used in cellulose mercerization before making fiber composites.

3.1. Noise Absorption Testing

The study aimed to observe the sound absorption coefficient based on varying filler content ranging from 0 to 8 wt.% The results suggested that the sound absorption coefficient was diverse across different frequency ranges. The 6 wt.% of filler content had the highest sound absorption coefficient at 0.9869, while polyester had the lowest at 0.832, as displayed in Figure 1. This indicates that the sound absorption coefficient is close to 1 and had an improvement of around 18.62% compared to polyester. Further observations discovered that the frequency absorption values at 2,268 Hz presented earlier than other composite filler content. This frequency was valid; good results were expected for the frequency ranges between $45.6 \leq f \leq 4{,}559$ Hz for coconut (Da-Silva *et al.*, 2019).

In Figure 2, it can be observed how the transmission loss in coconut fiber composites predicted by DB is affected by filler content. As we add more filler, the composite effectively counters the sound (dB), as the linear line suggests. The transmission loss values increase with the addition of filler content. However, the results reveal that only 2 wt.% of filler content demonstrated the highest sound (dB) absorbance, which then becomes lower and remains constant. This result was most likely caused by an uneven distribution of the fibers and agglomeration during composite fabrication. Therefore, to ensure the best sound-absorbing results, it is crucial to maintain an even distribution of the fibers during the fabrication process.

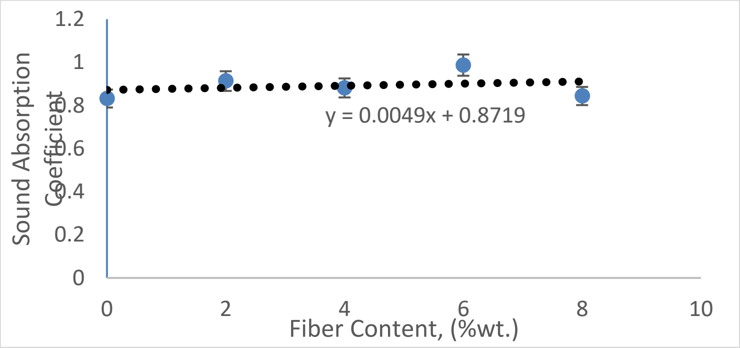

Figure 1 The sound absorption average of coconut fiber

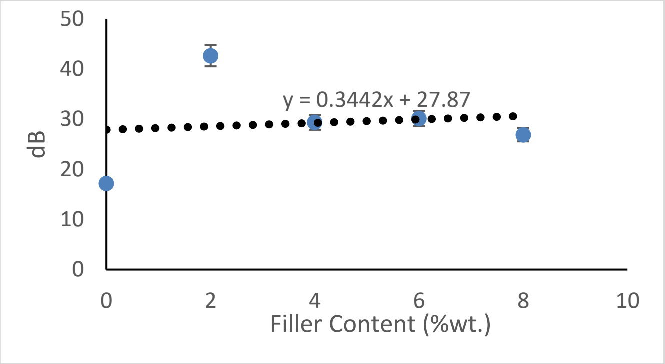

Figure 2 Transmission loss against filler content of coconut fiber

3.2. Numerical Analysis

3.2.1. Validation

This study aimed to validate a proposed simulation method by comparing it to experimental results. The simulation began by performing A-weighted Mic SPL to understand the distribution characteristics of thin HVAC channels, which were HVAC systems without composite treatment, to match the experimental results. The initial observation found that the A-weighted Mic SPL closely matched the recording level of the experimental results. This is shown in Figure 3, which demonstrates the relationship between reading performance from the HVAC channel and A-weighted Mic SPL within the frequency range of 1.25 Hz to 25 Hz. The maximum frequency of 25 Hz could produce an A-weighted Mic SPL of 58.165 dB, comparable to the experiment results, where the maximum was 58.1 from the equipment reading.

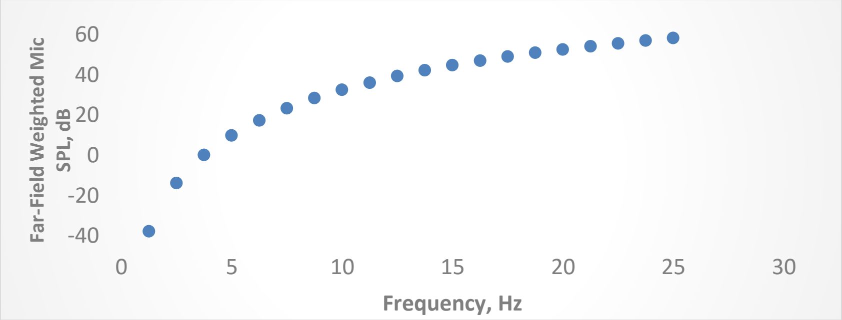

Figure 3 Far-Field weighted Mic SPL

3.3. A-weighted frequency band SPL Observation

This study utilized the numerical simulation for A-weight PSL and far-field phase (°) analysis on the HVAC channel treatment effect. Appendix 9 displays the contour distribution of the A-weighted frequency band SPL of inlet fresh air half-cut. The simulation predicts the measured A-weighted frequency band SPL within a combination of coconut fiber composite treatment, and most of the contour distribution was well met. In the A-weighted frequency band, the SPL distribution pattern was dominated by a solid HVAC channel and then distributed to the air, especially on the inlet fresh air part. The simulated A-weighted frequency level was higher when the area was near the open channel. For comparison, the simulated A-weighted frequency level without coconut treatment was higher than that measured with coconut treatment. It can be observed by plotting the A-weighted frequency band SPL graph against coconut fiber content (wt.%). The value in the contour was beginning higher at 0 wt.% and then became lower by adding the coconut fiber event; the fiber effect came down slowly. The plotting was observed at any single point inside the channel. Meanwhile, the neck area point inside the channel was focused on presenting the coconut fiber effect, making it a powerful solution that should be considered for any related issues, as illustrated in Figure 4.

Figure 5 displays how the far-field phase (°) is affected by coconut fiber. The analysis successfully demonstrated that the far-field phase (°) could be accurately analyzed with adding coconut fiber. The results indicated a decreasing trend in the far-field phase (°) as coconut fiber content increased under varied frequency loads. The fiber effect decreased dramatically when coconut content was at 8 wt.%. Notably, at a low frequency of 5 Hz, the far-field phase (°) was recorded higher in the inlet channel and vice versa. As a result, the simulation proves that coconut fiber composite treatment is an effective solution to achieve noise control, and this method could guide the experiment to control noise.

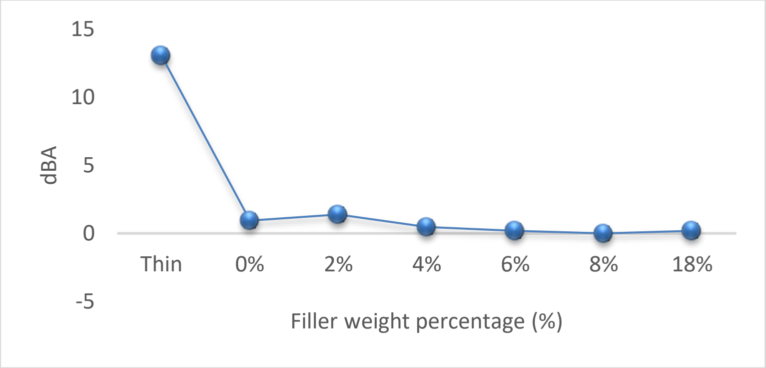

Figure 4 A-weighted frequency band SPL effect

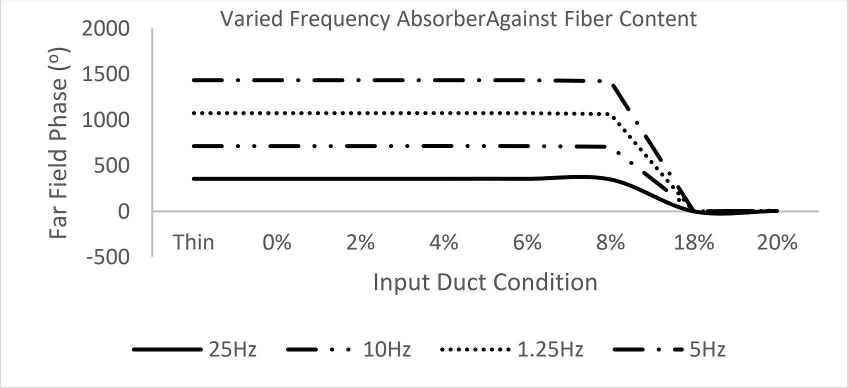

Figure 5 Far field phase (°) against inlet duct system treatment

3.4. Experimental

Table 2 presents the airflow readings obtained before installing the composite material when there was no fiber in the recirculation inlet area. The data was collected at a frequency of 10 s, with four data sets obtained at 0 seconds. Each type of blower speed was counted for 10 s to get the average airflow value. The first reading at 10 s recorded a value of 3.0 m/s, followed by 4.1 m/s at 20 s and 5.9 m/s at 30 s. The airflow readings were recorded at different blower speeds, including low, medium, and high speeds During the experiment, we measured the noise level of the HVAC system. We specifically focused on measuring the A-weighted SPL near the air outlets in the cabin. It is worth noting that each blower's speed had a different noise level. However, it is important to mention that the noise level did not fluctuate with changes in blower speed. The noise level was measured at a point in the recirculation inlet area where the volume was high. This point was then measured, and the noise level was discovered to vary before the composite treatment to obtain the actual value of the noise level. The distance from the diffuser was considered to test the noise level, and the actual value was obtained after measuring along a distance of 0.5 m. The noise measurement was conducted at noon for both experiments in a quiet environment to obtain the best result.

Table 2 Airflow reading without composite treatment

Fan Condition	Airflow, m/s	Temperature, ^{o}C	A-Weighted SPL, dB
Low	3.2	19.22	59.52
	2.97	18.17	59.47
	3.1	19.1	59.51
Medium	4.12	19.22	62.72
	4.05	18.17	62.67
	4.1	19.1	62.71
High	5.92	18.92	71.22
	5.87	18.87	71.17
	5.91	19.91	71.21

3.5. Treatment Composite Plate

The use of composite materials in a vehicle's HVAC system can enhance its efficiency and performance, as depicted in Appendix 10. By placing the composite treatment in the recirculation area where high sound levels are produced due to the blower's kinetic energy, a diverse approach can be taken towards improving the system.

Table 3 compares how airflow changes with different ratios of fiber. The experiment used fiber ratios of 0%, 2%, 4%, 6%, and 8% at low, medium, and high speeds. The anemometer sensor measured the airflow speed in front of the duct vent where the recirculation air area outlet is located. Consequently, each data result was recorded for 10 s for each fiber ratio at low, medium, and high speeds. It is crucial to obtain precise results to compare the airflow changes before and after composite treatment. Note that the results should remain constant. The collected data has revealed that the presence of the composite in the recirculation inlet area does not affect the airflow speed. Furthermore, the results have exhibited insignificant changes in the low, medium, and high airflow speeds. As per the data depicted in Table 3, the airflow speeds at low, medium, and high levels remained almost similar compared to those without treatment conditions. Hence, it can be observed that no disturbance was discovered in the airflow when the composite was located inside the critical point of the HVAC system. Therefore, the condition relies on the consistency and stability of airflow speeds while producing the variation speed.

Additional analysis has been carried out on the temperature observation, and the results are displayed in Table 4, which illustrates the temperature after the composite was attached to the recirculation inlet. The findings indicate negligible changes after the composite treatment to recirculation. The temperature observation was conducted on blower speed, ranging from low to high speed. Correspondingly, the outcomes revealed that the temperature dropped at high speed since the high speed produces higher airflow velocity that can cause the temperature to change abruptly when the temperature in climate control was switched to the lowest temperature. The temperature for each fiber ratio was recorded for 10 s in a constant sequence from low speed to high speed. Accordingly, the results were close to the temperature values in Table 4, as the temperature remained unchanged before and after the composite treatment.

By comparing various composite treatments, the temperature with different types of fiber ratios indicated the same reading between the temperatures before placing the composite in the recirculation inlet. This proves the temperature does not change if the composite is placed and before placing the composite in the recirculation inlet area. Notably, the temperature with various percentages may be constant in the value of the result, and the data was unchanging. The tabulated data from low speed to high speed has insignificant change. However, there was no big gap between the temperature change in all percentages of the fiber.

Table 3 Airflow speed measurement by composite treatment conditions

Fiber Content	Low Speed, m/s	Medium Speed, m/s	High Speed, m/s
0%	2.62	3.32	5.2
	2.57	3.27	4.97
	2.61	2.31	5.1
2%	2.62	3.52	5.2
	2.57	3.47	4.97
	2.61	3.51	5.1
4%	2.62	3.32	5.2
	2.57	3.27	4.97
	2.61	2.31	5.1
6%	2.62	3.32	5.2
	2.57	3.27	4.97
	2.61	2.31	5.1
8%	2.72	3.62	5.72
	2.67	3.57	5.7
	2.71	3.61	5.47

Further study focused on noise control. Figure 6 illustrates the comparison results of the noise level in dBs by various composite treatments. The findings are compelling and are highlighted in Appendix 9. The data suggests that the highest noise level occurred at 0 wt.% of composite treatment and increased with the velocity flow. However, the study also discovered that increasing the composite's fiber content reduced noise levels significantly. This trend is a crucial factor in controlling noise levels in the cabin. The recorded data indicates that the lowest noise levels occurred at 8 wt.% within 51 dB to 58.7 dB of the A-weighted scale. The method data suggests that the temperature is constant for every sample. Furthermore, the results can be accurately measured by measuring the time for every fiber ratio at 20 s from low speed to high speed and repeatedly taking the time for 0%, 2%, 4%, 6%, and 8%. In addition, these findings demonstrate the significance of controlling fiber content in the composite to reduce noise levels effectively.

Table 4 Temperature measurement by composite treatment conditions

Fiber Content	Low Speed, ᵒC	Medium Speed, ᵒC	High Speed, ᵒC
0%	19.42	19.1	18.52
	19.37	18.97	18.47
	19.41	18.98	18.51
2%	19.72	19.62	19.52
	19.67	19.57	19.47
	19.1	19.61	19.51
4%	18.52	19.42	18.42
	18.47	19.37	18.37
	18.51	19.41	18.41
6%	19.42	18.92	18.92
	19.37	18.87	18.87
	19.41	18.91	18.91
8%	19.42	19.42	18.92
	19.37	19.37	18.87
	19.41	19.41	18.91

The noise that enters a vehicle's HVAC system can come from various sources (Chen *et al.,* 2023; Deryabin, 2022). Firstly, the noise generated by the engine, which reverberates through the vehicle's structure, can cause a rumbling or buzzing effect in the HVAC components. Additionally, the noise generated during air intake through intake systems and exhaust noise produced during combustion can contribute to cabin acoustics and impact the HVAC components. Furthermore, specific components in the car, like fans, pumps, and belts, can produce distinct noises that affect the HVAC system. Finally, squeaks and vibrations caused by incorrectly installed or loose HVAC systems or vehicle components can amplify the overall noise level of the HVAC system in vehicles. This phenomenon is similar to that reported by previous researchers (Singh and Mohanty, 2018). They proposed using jute felt and waste cotton for noise control in the HVAC system. After conducting various trials, a treatment was identified that effectively minimized noise while minimizing costs and weight. This treatment was applied to the typical HVAC noise spectrum at medium-high blower speed, resulting in a 4 dB reduction in SPL at the passenger's ear position, with a minimum reduction of 3.6 dBs per blower speed. Moreover, the treatment led to a substantial 24% reduction in loudness level, equivalent to 7 sones. Consequently, it has been determined that treating the HVAC unit makes it safer for prolonged exposure to sound. Therefore, it can be concluded that treating HVAC sounds significantly reduces the likelihood of their occurrence. Furthermore, the application of this treatment has greatly enhanced the sound quality within the vehicle's interior space. This leads to a considerable reduction in the annoyance caused by the HVAC sound and the overall vehicle interior soundscape.

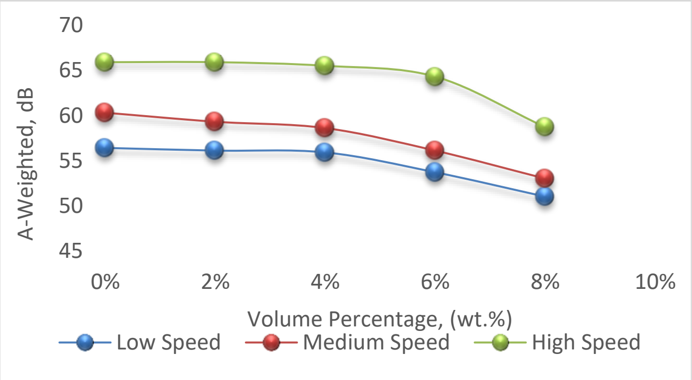

Figure 6 Noise reading with composite treatment

4. Conclusions

The study discovered that using coconut fiber can effectively reduce HVAC noise, resulting in a quieter and more comfortable atmosphere for car occupants. The numerical analysis demonstrated that coconut fiber is highly effective at absorbing sound on high-contribution sources of noise treatment (11 dBA). The results revealed that the airflow percentage difference between before and after the composite treatment for an 8% fiber ratio in low-speed airflow was 6.67%. In medium speed, the percentage difference was 12.20%, while in high-speed airflow, it was 6.78%. For temperature, the percentage difference between before and after the composite treatment for an 8% fiber ratio in low speed was 1.04%, while in medium and high-speed airflow, the percentage difference was 0%. Furthermore, the noise measurement percentage difference between before and after composite treatment of 8% fiber ratio for low speed was 14.28%. Similarly, the fiber ratio for medium speed and high speed was reduced by 15.47% and 17.56%, respectively. The noise measurement results demonstrate a significant difference between before and after the composite treatment. Therefore, future research should prioritize the optimization of the coconut fiber ratio at different speeds to achieve maximum efficiency in reducing noise. Additionally, it is essential to thoroughly examine long-term durability and biodegradability to ensure sustainability throughout prolonged usage. Comparative evaluations with other NRs, such as jute, cotton, and flax, can help establish the most efficient material for controlling HVAC noise.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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