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Muhammad Zulkarnain, Lubis M. Sobron Yamin, Hafizi Teo, and Ahmad Afham

***Abstract*—Outdoor air conditioning units are significant contributors to environmental noise pollution, primarily due to aerodynamic fan noise, compressor-induced structural vibrations, and complex airflow interactions. This study presents a comprehensive investigation into the acoustic and vibration performance of a 1 HP residential air conditioning outdoor unit, integrating numerical simulation and experimental validation. A Finite Element Analysis (FEA) approach using ANSYS was employed to model the Sound Pressure Level (SPL) distribution and structural-acoustic interaction. Correspondingly, modal and harmonic response analyses were conducted to simulate vibrational behaviour under operational conditions, incorporating covered treatment using coconut husk for noise attenuation. Results confirm that the proposed treatment achieves measurable noise attenuation without compromising system performance, with up to a 5 dB reduction in A-weighted SPLs. Overall, this research underscores the potential of passive noise control strategies using sustainable materials and offers a practical framework for improving the acoustic performance of residential outdoor systems.**

***Index Terms*—noise control, passive noise mitigation, finite element analysis, coconut husk.**

I. Introduction

AIR conditioning and heating units produce noise from multiple sources, including vibrations from the compressor, electric motor, and fan [1]-[3]. Specifically, compressor vibrations are typically modelled as monopole sources, motor vibrations as dipole sources, while fan noise exhibits both dipole characteristics and aerodynamic noise components resulting from airflow interactions [4]. In addition, mechanical coupling between these vibrating components and the cabinet panels can amplify noise through increased structural radiation [5]-[8]. The interaction of airflow with internal elements such as the cooling coil, tubes, and grills further contributes to overall noise levels [8]. Despite extensive research focusing on noise reduction in indoor air conditioning units, the acoustic behaviour and noise control of outdoor units remain significantly underexplored [9]. Given the importance of minimising environmental noise pollution, especially from outdoor units that directly impact outdoor and neighbouring environments, further comprehensive studies are essential. This aims to understand the specific noise mechanisms, interactions, and mitigation strategies relevant to outdoor air conditioning systems.

Mechanical and acoustical coupling between key components, such as fans, compressors, and electric motors, and the cabinet panels of air conditioning units can significantly amplify vibration-induced noise. Among these, electric motors are frequently identified as the primary source of annoyance, generating pronounced vibrations at 120 Hz and its harmonics, resulting from magnetic force fluctuations at twice the electrical line frequency [1]. In essence, this highlights the need for targeted, effective noise management strategies in such systems. Specifically, the outdoor unit of an air conditioner emits three dominant types of noise: (1) aerodynamic noise from fan blades caused by pressure fluctuations and airflow turbulence, which is typically the most prominent; (2) high-frequency noise originating from the compressor, which warrants particular attention due to its sharp tonal characteristics; and (3) low-frequency structural vibrations transmitted through the cabinet [10]. Measurements presented in Table 1, conducted under different operating conditions, further confirm that the aerodynamic noise from the fan remains the highest across all periods, underscoring the need for focused noise-reduction strategies targeting fan-induced emissions. Furthermore, the measurements reveal consistently high noise levels throughout the day, with only slight variations. In addition, the data confirm that noise from several sources, such as fan-generated aerodynamic noise and low-frequency structural vibrations, is present across all periods. Essentially, this finding highlights the critical need for targeted noise control interventions focusing on the fan assembly and airflow path, which are key contributors to the overall noise profile of the outdoor unit.

Extensive studies on fan noise have elucidated key generation mechanisms and mitigation strategies [11]-[13]. Minor geometric modifications often yield limited acoustic benefits and may impair aerodynamic efficiency. Notably,

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repositioning the centrifugal impeller cut-off significantly reduces noise without compromising performance. In particular, flow separation at the shroud and blade suction sides is a primary source of low-frequency noise in centrifugal fans [14]. While in-duct sound power data is commonly available, estimating radiated noise from housing and ductwork remains complex due to installation-dependent variables. For axial fans, dominant noise arises from blade-casing pressure fluctuations and turbulence. Contributing factors include inlet flow irregularities [16], boundary-layer separation, trailing-edge interactions, tip and hub secondary flows, and vortex shedding from tip gaps. A comprehensive understanding of these phenomena is essential for optimising fan design and enhancing acoustic and energy performance in Heating, Ventilation, and Air Conditioning (HVAC) systems.

TABLE I
MEASURED NOISE LEVELS OF OUTDOOR UNIT

Noise Level (dBA)	Operating Period	Description	Observation
65	Morning	All outdoor unit components Operational	Highest noise level recorded; dominanted by fan noise
64	Afternoon	All outdoor unit components Operational	Slight reduction observed; aerodynamic noise remains dominant
63	Evening	All outdoor unit components Operational	Lowest measured level; fan remains key noise contributor

Recent studies have advanced noise mitigation strategies for outdoor units of split-type air conditioners. For instance, Hu [17] asserted that circular outlet louvres reduce noise by smoothing airflow and minimising turbulence. Meanwhile, Zhou [18] noted that two-phase flow in Electronic Expansion Valves (EEVs) significantly increases noise, emphasising the need to address flow conditions during design. Moreover, Ruebeling [19] identified capillary tube outlets as major sources of flow-induced noise, while Kim [20] highlighted the influence of pipe layout and refrigerant properties on two-phase noise near EEVs. Additionally, to address dominant low-frequency noise (< 200 Hz), Dandsena et al. [21] employed Helmholtz resonator arrays, achieving a 7-dB reduction. Sonic crystal barriers with resonant elements [22], [23], and LRSC window barriers [24] offer effective broadband attenuation and natural ventilation, presenting viable solutions for noise-sensitive urban environments. Furthermore, advances in Active Noise Control (ANC) have demonstrated promise in reducing compressor noise in air conditioning systems. Similarly, lightweight active casings combined with Foam Metal Casing Treatment (FMCT) effectively suppress radiated and structure-borne noise while enhancing system efficiency [25]. Following this, Thielecke [26] introduced Current Shaping (CS) to optimise compressor drive currents, achieving significant vibration reduction via a dedicated test bench. Likewise, Load Torque Compensation (LTC) has proven effective in attenuating even-order vibrations in twin rotary compressors, with performance varying with pressure differential and rotational speed [27]. Interestingly, these integrated ANC strategies offer a robust framework for developing quieter, energy-efficient outdoor units.

Natural fibres provide sustainable, cost-effective solutions for HVAC noise reduction owing to their acoustic properties and environmental advantages. Accordingly, the coconut husk selected for this study offers moderate sound absorption at mid-to-high frequencies and is plentiful in tropical regions, making it a feasible alternative to synthetic materials [28]. Other fibres, such as kenaf [29], jute [30], hemp [31], and flax, also exhibit effective damping across various frequency ranges and promote circular economy principles. On a similar vein, coconut husk is notable for its low cost, ease of installation, and biodegradability. Initial analysis suggests up to a 5 dB noise reduction with minimal effect on system performance. Still, its limited absorption at low frequencies indicates that hybrid configurations may be necessary for wider applications. Nonetheless, its scalability and compatibility with residential HVAC casings make it suitable for retrofitting, although industrial use might require composite enhancements. Its lightweight nature and ease of integration into existing casing designs support retrofitting and modular implementation. However, for larger or industrial systems, the material's acoustic limitations, especially in the low-frequency range, may require composite layering with other absorptive materials or design modifications to enhance effectiveness. Despite this, coconut husk was preferred as the primary material for noise mitigation due to its sustainability, cost-effectiveness, and local availability. As an agricultural byproduct, coconut husk is readily found in tropical regions such as Malaysia and Indonesia, minimising the need for synthetic or imported materials [32]. Its use promotes waste valorisation, supports circular economic principles, and reduces environmental impact. Compared with traditional acoustic materials such as mineral wool or synthetic foams, coconut husk is a low-cost alternative that requires minimal processing.

Outdoor air conditioning units are increasingly recognised as significant contributors to environmental noise pollution, particularly in urban residential areas. These units generate complex noise profiles arising from aerodynamic fan turbulence, compressor-induced structural vibrations, and airflow interactions within the cabinet. While substantial research has addressed noise control in indoor HVAC systems, the acoustic behaviour and mitigation strategies for outdoor units remain underexplored. Correspondingly, this study aims to bridge that gap by investigating the acoustic and vibrational performance of a 1 HP residential outdoor air conditioning unit through a combined numerical and experimental approach. Specifically, it evaluates the effectiveness of coconut husk, a biodegradable, locally available natural fibre, as a passive noise mitigation material. The research objectives include modelling Sound Pressure Levels (SPLs) and structural vibrations using Finite Element Analysis (FEA), validating results through experimental measurements, and assessing the impact of coconut husk treatment on noise attenuation and vibration isolation. Meanwhile, key research questions focus on whether coconut husk can significantly reduce noise without compromising system performance, how its thickness and configuration influence acoustic absorption, and how it compares with conventional materials such as mineral wool and recycled Polyethene Terephthalate (PET). This work aligns with proper methods by integrating sustainable engineering practices, computational modelling, and experimental validation to address real-world challenges in mechanical and environmental acoustics.

II. METHODS

A. Numerical Analysis

A numerical design approach was applied to the outdoor unit, incorporating documented loudness levels and SPL distribution near the source. FEA using ANSYS evaluated the composite structure to minimise SPL. The acoustic solver utilised natural frequencies and mode shapes derived from modal analysis. Subsequently, the dynamic response was computed by solving the equation of motion, treating nodal acceleration, velocity, and displacement as unknowns.

$$.[M\{\ddot{u}\}+[C]\{\mathring{u}\}+[K]\{u\}=\{f(t)\} \quad (1)$$

Here, M, $\ddot{u}$, C, $\dot{u}$, K, u, and f represent the mass matrix, acceleration vector, damping matrix, velocity vector, stiffness matrix, displacement vector, and external load vector, respectively. For harmonic motion, such as the oscillation of a simple spring-mass system, ANSYS employs the formulation represented by equation (2). This type of motion is periodic and is characterised by its amplitude, frequency, and phase angle.

$$x = Asin(\omega t + \theta). \quad (2)$$

In this context, A, ω, and θ represent the amplitude, angular frequency, and phase angle, respectively.

Computational Domains and Details

The computational domain includes the fresh-air inlet head and channel, with the motor and compressor positioned as primary noise sources. Geometric details of the inlet and domain dimensions (570 cm × 600 cm × 780 cm) are presented in Fig. 1(a) and Fig. 1(b), respectively. Meanwhile, noise reduction using coconut husk material is evaluated in Fig. 1(c).

Acoustic Simulation Setup

To accurately model acoustic pressure fields, a constant excitation frequency of 25 Hz was applied at the inlet boundary, perpendicular to the flow. This frequency aligns with typical structural vibration modes and dominant airborne noise components. Furthermore, material-specific properties, particularly density, were used to simulate sound propagation characteristics.

An acoustic domain was defined with radiation boundary conditions to simulate free-field behaviour and eliminate non-physical reflections. Concurrently, composite materials were integrated into the geometry to evaluate noise treatment strategies. A solid-fluid interface separated the air domain from structural components, and a harmonic mass source initiated the simulation. Following this, coconut husk was applied to the recirculation inlet and airflow paths, with internal cabinet cavities near the blower intake also treated, as illustrated in Fig. 1(c).

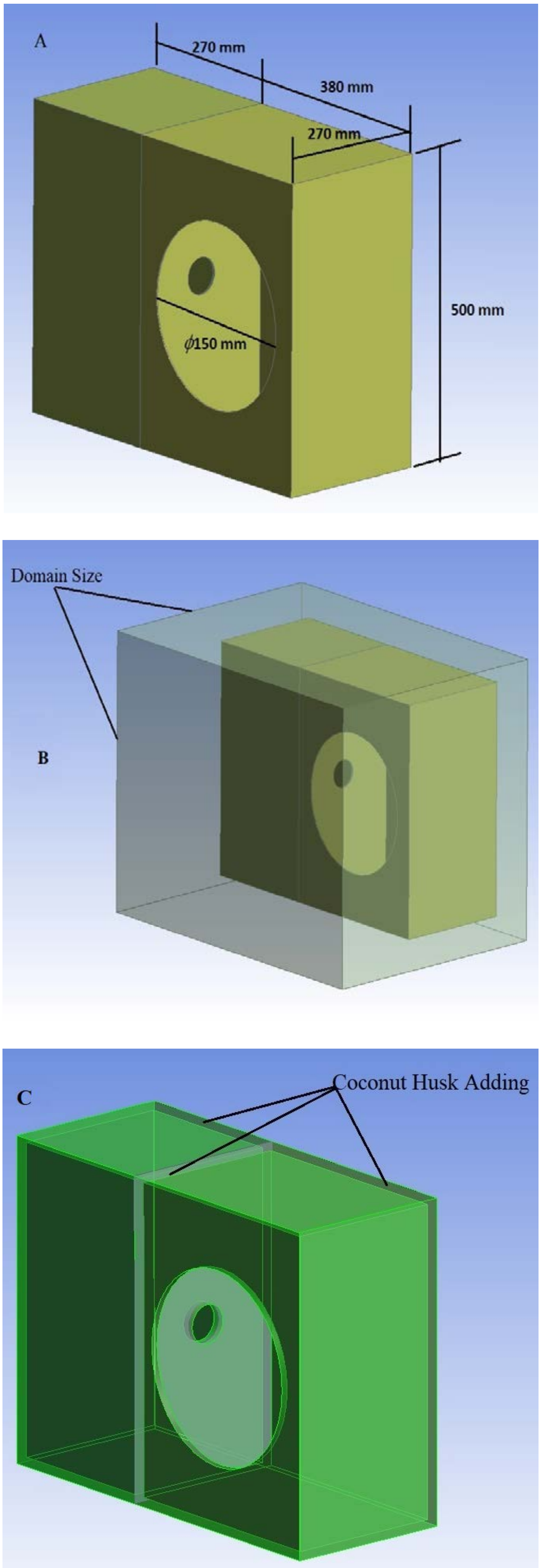


Fig. 1. Computational domain of the fresh air inlet head: (a) geometric dimensions, (b) overall computational domain size, and (c) noise reduction treatment using coconut husk.

B. Experiment Setup

This study focuses on a 1 HP residential split-type air conditioning unit, commonly used in urban settings. Noise emission was evaluated under three scenarios to assess casing and treatment effects. In Scenario 1, the cabinet was lined with coconut husk to test its noise reduction potential. In comparison, Scenario 2 served as the baseline, with the cabinet installed and the compressor mounted on a sensor-equipped test rig, but without additional treatment.

Coconut husk material setup

Coconut husk fibres were sourced locally from Malaysian farms and processed by shredding coconut husks. Acoustic performance was evaluated using an impedance tube setup with ACUPRO v4.5, in accordance with ISO 10534-1 and ASTM E2611. The 38 mm stainless steel tube, equipped with four microphones, measured sound absorption and transmission loss across 100-5,000 Hz. Two sample configurations, Load A and Load B, were evaluated to assess the material's acoustic behaviour under varying conditions. This enables comparative analysis of absorption and transmission characteristics.

Noise levels were measured at the upper, central, and lower sections of the outdoor unit to capture spatial variations. An iPad with a dBA meter app was utilised for preliminary readings due to its portability. To ensure accuracy, measurements were calibrated against a professional sound level meter under identical conditions. As a result, a consistent deviation of 2.6 dB was observed and applied as a correction factor to all iPad-based readings.

Fig. 2 illustrates the experimental setup for field noise measurements, with calibration steps presented in Fig. 3. Coconut husk was installed around the compressor inside the cabinet to enhance noise absorption. Noise levels were recorded and analysed to determine average and peak values under each condition, providing a practical evaluation of the material's effectiveness. Moreover, Fig. 4 presents noise levels across different periods, with the highest levels observed in the morning.

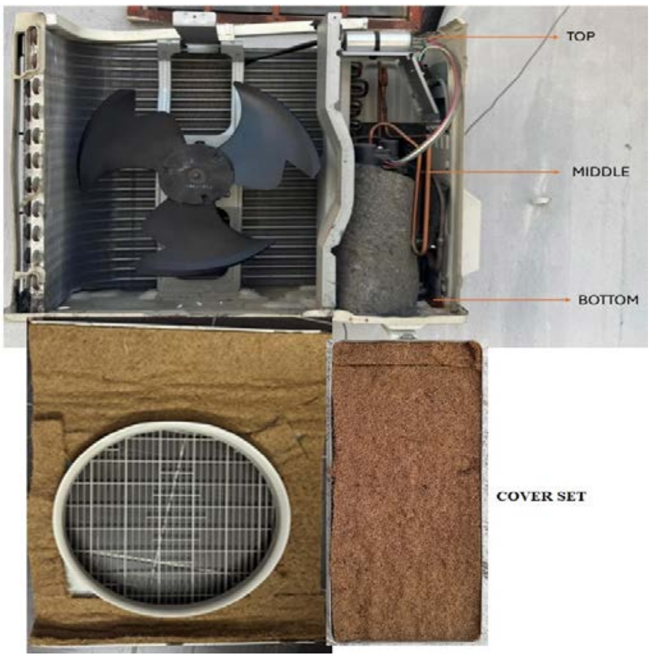


Fig. 2. Coconut Husk Setup at the Outdoor Unit

Fig. 3. Calibration Setup Using iPad and Sound Level Meter

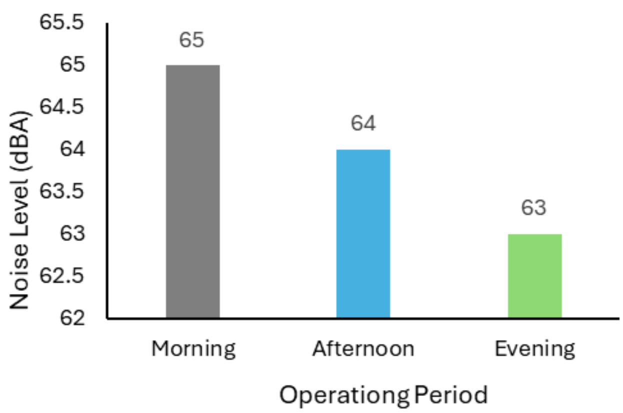


Fig. 4. Noise Levels of Outdoor Air Conditioner Unit During Different Periods

Identification Vibration Setup

Vibration velocity Root Mean Square (RMS) was measured across various mounting configurations, including different sizes and types. The setup included a high-precision vibration analyser with spectral analysis software, as well as a manifold gauge for refrigerant pressure monitoring. Interestingly, the compressor test rig allowed flexible mounting adjustments, while a control unit simulated diverse operating conditions. Table 2 lists the equipment used for data collection.

TABLE II
LIST OF EQUIPMENT AND DESCRIPTION

Equipment	Description
m+p VibPilot	A compact, high-performance hardware platform used for vibration measurement, control, and dynamic signal analysis, integrated with specialised software.
Manifold Gauge	A diagnostic tool used to measure refrigerant pressure in HVAC systems, essential for monitoring and maintaining system performance.

Vibration analysis was performed on a 1 HP split-unit compressor mounted on rubber isolators. Accelerometers were placed near mounting points and brazed joints to monitor transmission and detect anomalies. Accordingly, measurements were repeated three times per configuration under controlled conditions. The system was charged with

R22 refrigerant (~65 psi), monitored via a manifold gauge. In addition, vibration data were collected using a vibration analyser, as depicted in Fig. 5 and Fig. 6.

A comparative analysis was conducted to evaluate the effectiveness of various anti-vibration configurations. Priority was given to setups that achieved maximum vibration reduction while maintaining noise and energy performance. All measurements and observations were systematically documented. Subsequently, results were compiled into a comprehensive report with tables and graphs illustrating the impact of each configuration on vibration levels.

Following the baseline assessment, anti-vibration configurations were modified by varying rubber mount properties, including size, thickness, diameter, and shape. For each setup, vibration amplitude, frequency, phase, acceleration, temperature, noise level, and energy consumption were recorded using designated instruments. Following this, data were analysed using vibration analysis software to identify the most effective configuration for minimising vibration and optimising system performance.

As displayed in Fig. 7, vibration sensors were placed at critical transmission points: Point 1 near the rubber mount and compressor base nut, and Point 2 at the inlet and outlet of the copper piping. These locations were selected to capture key vibration pathways within the system.

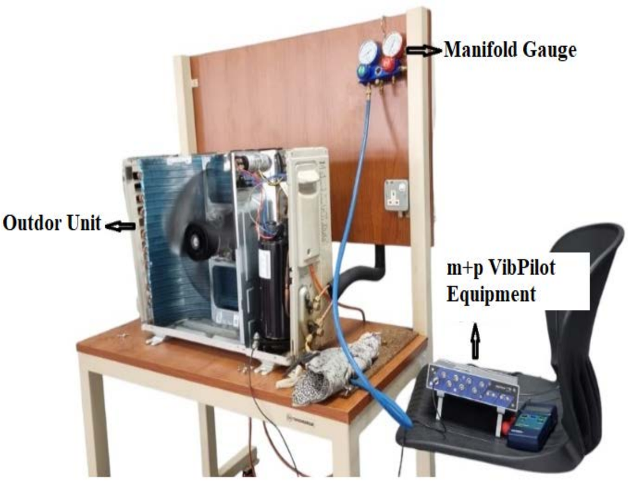


Fig. 5. Experimental setup

Fig. 6. Vibration sensor location

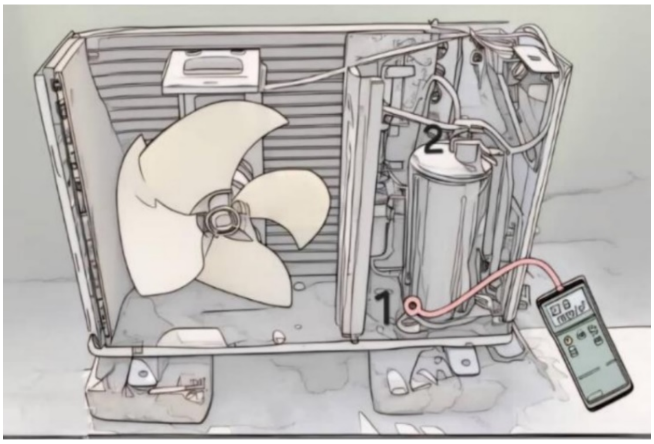


Fig. 7. Location for vibration measurement of the compressor.

III. RESULTS AND DISCUSSIONS

A. Numerical Analysis

Validation

Comparative validation was performed between simulation outputs and experimental measurements to ensure the robustness of the methodology. A-weighted SPLs were computed for untreated outdoor channels within the 1.25-25 Hz frequency range. As illustrated in Fig. 8, the simulated SPL trend closely aligned with the experimental data, reaching a peak of 66.12 dB at 25 Hz, compared to the measured 65 dB. This close agreement validates the model's accuracy in capturing the dominant acoustic behaviour. Concurrently, A-weighting was adopted to emphasise relevance to human auditory perception, thereby strengthening the applicability of simulation findings to real-world HVAC conditions.

Subsequent numerical analyses assessed the effect of coconut husk treatments on channel acoustics. SPL contour plots (Fig. 9) revealed that untreated configurations exhibited elevated noise near the outlet, while husk-treated channels consistently demonstrated attenuated SPL values across the domain. In general, increasing coverage proportionally reduced SPL at multiple monitoring points, verifying the effectiveness of coconut husk as a low-cost acoustic treatment material. Numerical simulations were conducted to evaluate the acoustic performance of coconut husk-treated outdoor channels using A-weighted SPL analysis. Fig. 9 illustrates the SPL contours for both untreated (Fig. 9a) and treated (Fig. 9b) configurations. Remarkably, the simulations effectively captured the SPL distribution, revealing elevated levels near the outlet in the untreated scenario. In contrast, applying coconut husk treatment resulted in a marked reduction in SPL throughout the channel, particularly at designated monitoring points. A progressive increase in treatment coverage was associated with greater SPL attenuation across varying frequency loads, thereby validating the material's efficacy for noise mitigation in HVAC systems. The SPL contour maps consistently demonstrated that untreated configurations exhibited higher SPL values, whereas treated configurations showed significant reductions. Notably, these effects were evident across multiple locations within the channel and at external monitoring points, where the influence of the coconut husk treatment was most pronounced.

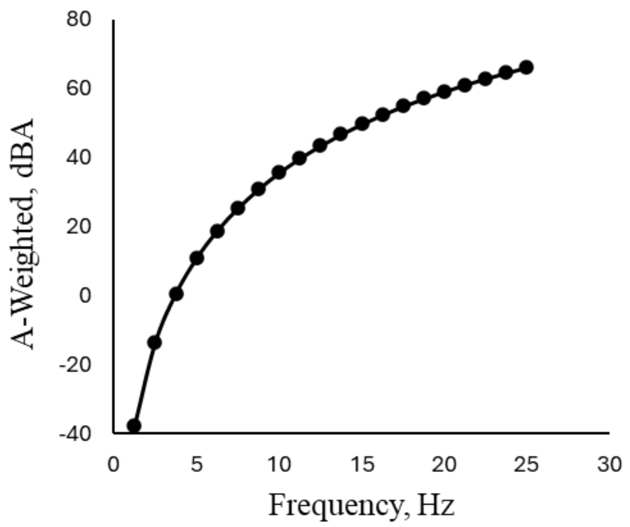
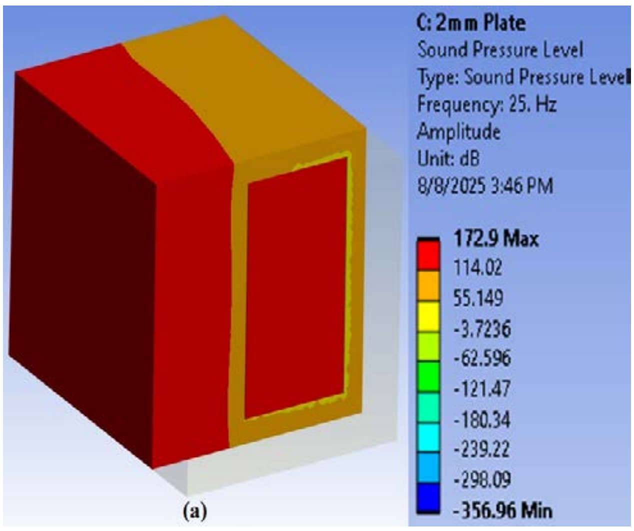


Fig. 8 Far-field A-weighted microphone sound pressure level (Mic SPL).

The influence of coconut husk thickness on A-weighted SPLs within the 1.25-15 Hz frequency range was systematically examined. Fig. 10 presents the SPL response for varying husk thicknesses. Results indicate a consistent decrease in SPL with increasing frequency and husk thickness. The untreated 2 mm plate exhibited minimal acoustic absorption, whereas the addition of 5 mm, 10 mm, and 15 mm husk layers progressively enhanced attenuation, with the 15 mm configuration achieving the most substantial reduction. These findings demonstrate that increased husk thickness significantly improves low-frequency noise absorption, reinforcing its potential as a sustainable acoustic insulation material. Building on this, the attenuation effect was especially pronounced at lower frequencies, where material differences were more evident. Moreover, a clear inverse relationship between husk thickness and SPL was observed. This confirms that layer thickness plays a critical role in enhancing acoustic performance for low-frequency noise control applications.



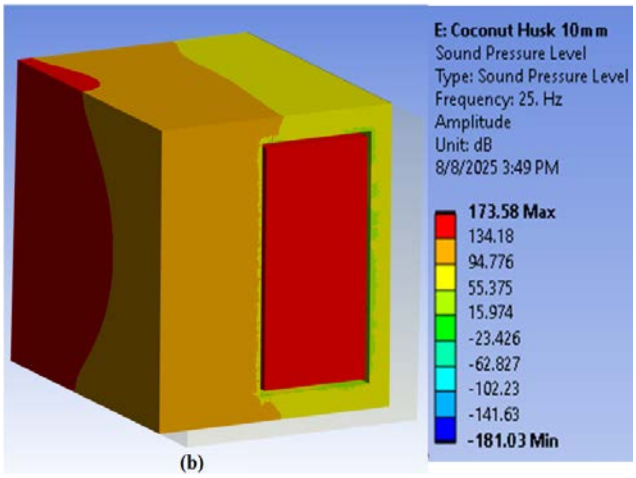


Fig. 9. Effect of A-weighted frequency band on sound pressure level (SPL): (a) 0 treated and (b) coconut husk treated.

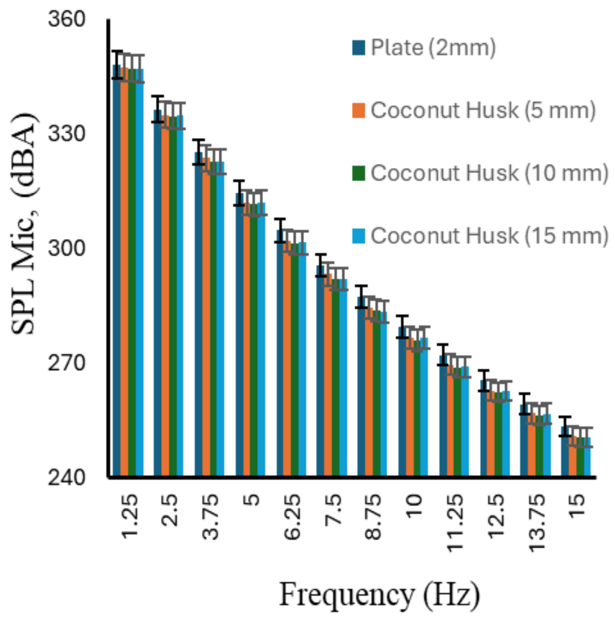


Fig. 10. Effect of coconut husk thickness on Sound Pressure Level (SPL) against a frequency range.

B. Experimental Results

Coconut Husk

Impedance tube tests conducted under Load A and Load B demonstrated a significant influence of material configuration on absorption performance. Notably, Load B consistently outperformed Load A across the 100-5,000 Hz frequency range, with particularly noteworthy results at 125 Hz (a 33 dB reduction) and at 200 Hz (a 50 dB reduction) (see Fig. 11). This underscores the significance of optimising mounting configurations to enhance low-frequency absorption.

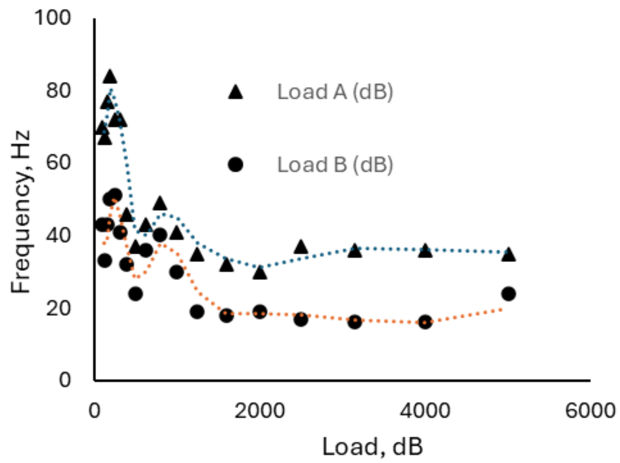


Fig. 11. Frequency vs Sound Pressure Level (Load A and Load B)

Noise measurements were calibrated using a sound level meter (dB), with both measurement devices positioned identically to ensure consistency. A correction factor of 2.6 dB was applied to all readings obtained from the iPad to align them with the calibrated reference. Table 3 summarises the adjusted noise levels and sound absorption performance of coconut husk under various casing conditions. Concurrently, the application of coconut husk treatment reduced the average SPL from 67 dB (without cabinet) to 62 dB (with treated cabinet), while the maximum SPL decreased from 70 dB to 65 dB. This corresponds to an approximate 7.46% reduction in average SPL, resulting in a perceptible loudness decrease of nearly 30%, a significant improvement for residential acoustic applications. Collectively, these results confirm the effectiveness of coconut husk as a sustainable acoustic insulation material, particularly in reducing ambient noise levels in enclosed environments.

TABLE III
MEASURED NOISE LEVELS MEASURED

Condition	Up (dB)	Middle (dB)	Down (dB)	Average (dB)	Max (dB)
With Coconut Husk	62	63	61	62	65
Without Coconut Husk	64	65	63	64	67
Without Case	67	66	68	67	70

The effect of varying coconut husk content on sound absorption performance was evaluated, as depicted in Fig. 12. In particular, the analysis focused on absorption coefficients across the 200-1,200 Hz frequency range for coconut husk contents ranging from 2 to 8 wt.%. The configuration with 6 wt.% coconut husk exhibited the highest absorption coefficient (~0.98), indicating near-complete attenuation of high-frequency noise. Conversely, lower contents (2–4 wt.%) demonstrated reduced absorption performance, while the 8 wt.% configuration presented a slight decline, suggesting a saturation threshold beyond which additional husk content does not enhance acoustic performance. Overall, these results identify 6 wt.% as the optimal composition for high-frequency noise control, likely due to an optimal balance between porosity and fibre distribution. In Experiment 1, the application of coconut husk to the compressor cabinet yielded the lowest recorded noise level, averaging 62 dB. This represents a 2 dB reduction compared to the untreated cabinet and a 5 dB reduction relative to the configuration without any cabinet. Although the absolute reduction is modest, it may not produce a substantial perceptual improvement in loudness. Nonetheless, the findings reinforce the potential of coconut husk as a sustainable material for targeted acoustic insulation applications.

Experiment 2, conducted using an impedance tube setup, investigated the frequency-dependent behaviour of SPLs under two loading conditions. The results revealed a consistent decline in SPL with increasing frequency. For Load A, the highest SPL was recorded at 84 dB at 200 Hz, while the lowest was 35 dB at 5,000 Hz. Meanwhile, Load B followed a similar trend but consistently exhibited lower SPL values across all frequencies compared to Load A. These observations suggest that coconut husk demonstrates improved sound absorption at higher frequencies. However, its effectiveness remains limited in the low-frequency range, which is typically dominant in noise emissions from outdoor HVAC units. In essence, this highlights the need for further optimisation of the material for low-frequency noise control applications.

The combined findings from Experiments 1 and 2 suggest that coconut husk provides limited noise reduction for outdoor air conditioning units. In particular, the modest SPL reduction observed in Experiment 1 is consistent with the impedance tube results from Experiment 2, which revealed poor absorption performance at low frequencies. Given that outdoor HVAC units predominantly emit low-frequency noise, the effectiveness of coconut husk as an acoustic insulator is inherently constrained. Notably, the material met the ISO sound absorption threshold ($\alpha > 0.5$) only at frequencies above 1,250 Hz, indicating its suitability primarily for high-frequency noise attenuation. Additional tests conducted without the cabinet enclosure further emphasised the critical role of casing design in overall noise control. They also highlighted the limited contribution of natural absorbers such as coconut husk to mitigating low-frequency emissions.

A parametric evaluation of husk content (2-8 wt.%) indicated that 6 wt.% provided the highest absorption coefficient (~0.98 at 200-1,200 Hz), surpassing ISO thresholds for high-frequency absorption ($\alpha > 0.5$). However, performance decreased at 8 wt.% due to reduced porosity from fibre densification (Fig. 12). This indicates that optimal fibre density enhances absorption, while oversaturation compromises performance. Despite these advantages, coconut husk exhibited limited performance below 1,250 Hz, aligning with impedance tube findings. Since HVAC outdoor units primarily emit low-frequency tonal noise, the effectiveness of coconut husk is constrained. Nevertheless, its high-frequency absorption efficiency positions it as a viable material for residential indoor noise control. Despite these advantages, coconut husk exhibited limited performance below 1,250 Hz, aligning with impedance tube findings. Since HVAC outdoor units primarily emit low-frequency tonal noise, the effectiveness of coconut husk is constrained. Nevertheless, its high-frequency absorption efficiency positions it as a viable material for residential indoor noise control.

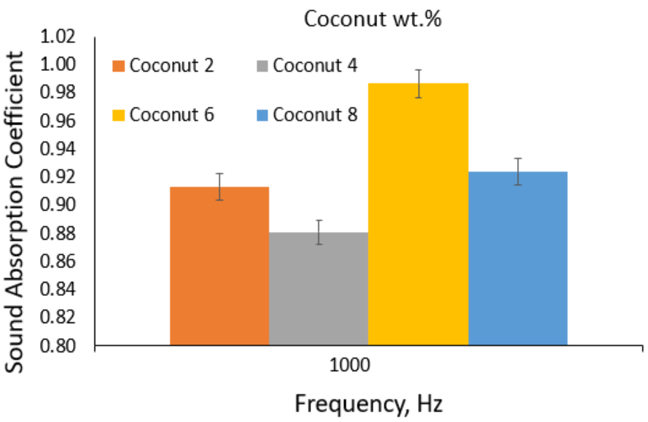


Fig. 12. The comparison of sound absorption coefficients by varying the coconut content.

Vibration Treatment

Vibration measurements presented in Table 4 reveal consistent patterns across sensor locations, with variations corresponding to specific mounting and structural features. As such, higher vibration velocities were observed near mounting points, indicating strong transmission pathways for mechanical vibrations. In contrast, lower readings at copper joints suggest reduced propagation in those regions. These results are consistent with expected compressor dynamics, confirming that mounting structures serve as primary conduits for vibration transmission. Supporting plots further illustrate the influence of mounting conditions and underscore the importance of strategic sensor placement for accurate vibration diagnostics and system evaluation.

TABLE IV
VIBRATION VELOCITY RMS

Mounting Type	Sensor Location	1 (mm/s)	2 (mm/s)	3 (mm/s)	Ave. (mm/s)
Original	Bottom	9.467	9.576	9.791	9.611
Rubber	Top	8.083	8.163	8.193	8.146
New	Bottom	5.864	5.656	5.680	5.733
Rubber	Top	4.923	4.179	4.135	4.412
Spring	Bottom	3.007	3.579	3.178	3.255
Head	Top	2.862	2.977	2.750	2.863

Vibration velocity measurements (mm/s) were obtained at the top and bottom of the compressor for three mounting configurations: original rubber, new rubber, and spring head. Each configuration was assessed in triplicate to ensure measurement reliability. The results, summarised in Table 5, indicate a progressive reduction in vibration velocity RMS values with improved mounting systems, with the spring head providing the lowest levels. Interestingly, this trend was consistent at both sensor locations, demonstrating that enhanced mounting designs effectively mitigate vibration transmission within the compressor assembly.

TABLE V
VIBRATION VELOCITY RMS

Sensor Location	1 (mm/s)	2 (mm/s)	3 (mm/s)
Bottom	9.611	5.733	3.255
Top	8.146	4.412	2.863

A comparative evaluation of three mounting systems demonstrated their influence on vibration isolation performance. The original rubber mount exhibited the highest vibration levels, indicating limited damping capability. In contrast, the newly designed rubber mount reduced vibration by over 40% at both sensor locations, offering improved isolation and cost-effectiveness. However, the shock-absorption spring head mount achieved the most substantial reduction, with vibration levels decreasing by 66.13% at the bottom and 64.84% at the top, as illustrated in Fig. 13. These results confirm the superior damping performance of the spring head mount, making it the most effective solution among the assessed configurations. While the new rubber mount presents a viable low-cost alternative, the spring head mount offers significant performance advantages that could enhance compressor reliability by minimising vibration-induced wear. Furthermore, its higher cost may restrict its use to critical systems where maximum vibration isolation is required.

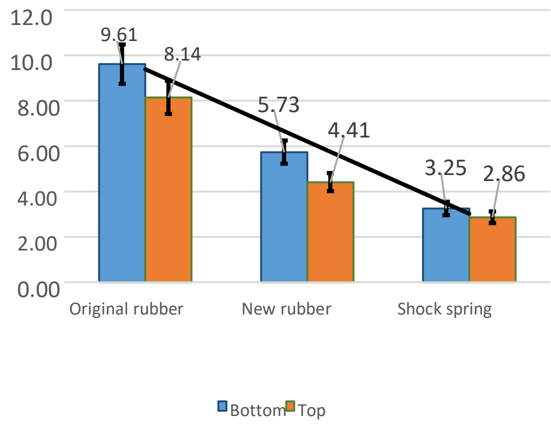


Fig. 13. Vibration velocity – Type of mounting graph

Experimental validation was conducted to ensure data reliability and adherence to industry standards. Each mounting configuration was tested three times at two sensor locations under consistent operating conditions (R22 refrigerant at 65 psi). Prior to testing, all sensors and the vibration analyser were calibrated to maintain measurement accuracy. Consistent with this, statistical analysis revealed minimal variability across trials, confirming the consistency of the recorded data. In addition, vibration levels were evaluated in accordance with ISO 10816 guidelines (Fig. 14) [33]. The improved mounting systems, namely the new rubber and spring head mounts, recorded RMS vibration levels below the 4.5 mm/s threshold, whereas the original rubber mount exceeded this limit. Taken together, these results validate the enhanced damping performance of the alternative mounting solutions and their compliance with vibration standards for rotating machinery.

Vibration measurements were conducted using three different mounting systems: original rubber, new rubber, and spring head. Results (Table IV, Table V) demonstrate a significant reduction in vibration transmission with improved mounts. Specifically, original rubber mounts recorded the highest vibration velocities (9.61 mm/s bottom, 8.15 mm/s top), exceeding ISO 10816 thresholds (≤4.5 mm/s). By contrast, spring head mounts reduced vibration by 66.13% (bottom) and 64.84% (top), achieving RMS levels of 3.26 mm/s and 2.86 mm/s, respectively, well within ISO limits. These findings highlight the spring head mount as the most effective isolation method, although the new rubber mount provides a cost-effective alternative with

~40% vibration reduction. Fig. 13 displays a comparative performance evaluation, confirming compliance with the ISO 10816 vibration standards [33].

C. Comprehensive Evaluation of Coconut Husk for HVAC Noise Control

Coconut husk is identified as a cost-effective and biodegradable material with moderate thermal insulation properties (0.045-0.055 W/m·K) [34], making it a viable option for HVAC noise mitigation. Its widespread availability in tropical regions provides an environmentally sustainable alternative to synthetic materials. Additionally, the porous microstructure enhances both acoustic absorption and thermal performance, although its effectiveness diminishes at lower frequencies. For residential-scale applications, coconut husk demonstrates satisfactory performance. However, larger-scale systems may require composite layering to achieve broader noise attenuation. At the same time, potential improvements include hybridisation with other natural fibres to further enhance acoustic characteristics and extend their applicability [35].

D. Comparative Analysis with Conventional and Sustainable Materials

In order to rigorously evaluate the acoustic performance of coconut husk as a noise-mitigation material, a comparative analysis was conducted with two commonly used alternatives: mineral wool and recycled PET fibre. These materials are frequently utilised in HVAC systems and building acoustics, making them a relevant benchmark for assessing the effectiveness of coconut husk. This comparison emphasises the potential benefits of coconut husk, particularly in terms of sustainability and environmental impact. Hence, by taking this approach, the study supports innovation in acoustic insulation technologies and encourages the adoption of eco-friendly practices within the industry.

Sound Absorption Coefficient Comparison

This study effectively integrates numerical simulations with experimental validation to evaluate the acoustic performance of coconut husk as a noise mitigation material. Field measurements and impedance tube tests conducted over the frequency range of 100 to 5,000 Hz demonstrated moderate sound absorption at mid to high frequencies. In addition, comparative analysis with mineral wool and recycled PET fibre indicated that coconut husk exhibits limited effectiveness at low frequencies, a critical consideration for HVAC noise control. Correspondingly, psychoacoustic metrics were employed to establish correlations between technical data and human auditory perception, while vibration analysis was utilised to quantify the pathways of structural noise transmission. Although coconut husk presents notable sustainability benefits, its acoustic performance, particularly at lower frequencies, requires further enhancement. Thus, the development of hybrid composites or modifications to the material may be necessary to improve low-frequency absorption and broaden its applicability in practical noise-control scenarios.

A constructive comparison was conducted against mineral wool and recycled PET fibre, which are widely adopted in HVAC noise control. Results demonstrated that while mineral wool and PET provide superior broadband absorption, coconut husk achieved near-total high-frequency absorption ($\alpha \approx 0.98$) at optimal density, with the added advantage of being biodegradable, low-cost, and locally available in tropical regions. Still, coconut husk exhibits poor low-frequency absorption, consistent with previous studies [32], [36]. While it matches or outperforms mineral wool and PET fibre at mid-to-high frequencies, hybrid reinforcement is required to improve low-frequency performance.

Interpretation and Applications

- Why results matter: Noise reduction enhances indoor comfort and equipment longevity, while vibration isolation extends compressor lifespan by mitigating fatigue failure.
- Limitations: Coconut husk is effective only above 1,250 Hz, limiting its standalone use in HVAC outdoor units. Thick layers (> 15 mm) may also be impractical in compact cabinet designs.
- Unexpected findings: The decline in performance at 8 wt.% coconut husk content suggests a reduction in porosity due to fibre densification, highlighting the need for optimised density ratios.
- Applications: Coconut husk is best suited for residential applications and indoor acoustic treatments, while vibration improvements are directly applicable to commercial HVAC compressors. Hybrid composites combining husk with PET or other natural fibres could address low-frequency limitations.

IV. CONCLUSIONS

This study integrated simulations and experimental approaches to assess the viability of coconut husk as a sustainable noise-control material for outdoor HVAC systems. The numerical models demonstrated that SPLs decreased with increased treatment using coconut husk. Nonetheless, both field tests and impedance tube assessments revealed that the material had limited effectiveness, particularly at low frequencies. Notably, coconut husk exhibited significant sound absorption only at frequencies above 1,250 Hz, rendering it less effective for mitigating low-frequency HVAC noise. Furthermore, a quantitative analysis indicated a progressive reduction in the RMS values of vibration velocity with the adoption of enhanced mounting systems. The original rubber mounting exhibited the highest vibration levels, exceeding 4.5 mm/s RMS, suggesting inadequate vibration isolation. Additionally, the vibration analysis confirmed that both the newly introduced rubber and spring head mountings significantly reduced vibration levels when compared to the original rubber mount. The spring head mounting, in particular, achieved over a 66% reduction and remained well within ISO 10816 limits, thereby demonstrating superior damping performance.

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