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Optimization of low frequency sound absorption coefficient in micro-perforated panels backed with Kenaf fibre using Response Surface Methodology and Multivariate Regression

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Abstract

The acoustic performance of micro-perforated panels backed with Kenaf fibre is highly dependent on the low-frequency sound absorption coefficient, which is influenced by complex interactions among material and structural parameters. We propose a systematic approach to optimize this coefficient by integrating Response Surface Methodology (RSM) and Multivariate Regression Model (MRM). The RSM captures nonlinear relationships and interactions between input variables, including linear, quadratic, and cross-term effects, while the MRM validates the model and identifies statistically significant factors. This dual-method framework enables a comprehensive analysis of how coefficients affect sound absorption, thereby facilitating the identification of optimal design parameters. The study addresses a critical gap in acoustic material optimization by providing a data-driven methodology that balances computational efficiency with empirical accuracy. Experimental validation demonstrates the robustness of the proposed approach, revealing key insights into the interplay between panel properties and acoustic performance. The results highlight the potential of Kenaf fibre as a sustainable alternative in noise control applications, offering practical guidelines for industrial implementation. Moreover, the methodology is adaptable to other composite materials, broadening its applicability in acoustic engineering. By bridging theoretical modeling and practical optimization, this work contributes to advancing the design of high-performance sound-absorbing materials.

Keywords: Tribal education, EMRS, different aspects

Introduction

Noise pollution has become a critical environmental concern, particularly in urban and industrial settings, necessitating the development of efficient sound-absorbing materials. Among these, micro-perforated panels (MPPs) have gained prominence due to their tunable acoustic properties and structural versatility [1]. The sound absorption mechanism of MPPs is primarily governed by Helmholtz resonance, where incident sound waves interact with the perforations and backing cavity to dissipate energy [2]. However, achieving optimal low-frequency absorption remains challenging due to the complex interplay between material properties, geometric parameters, and backing configurations.

Traditional MPPs often incorporate synthetic porous absorbers, such as glass wool or foam, to enhance their acoustic performance [3]. While effective, these materials raise sustainability concerns, prompting research into natural alternatives. Kenaf fibre, a biodegradable and renewable resource, has emerged as a promising candidate due to its favorable sound absorption characteristics and mechanical properties [4]. Recent studies have demonstrated that Kenaf-based composites exhibit competitive acoustic performance, particularly in the low-frequency range, where conventional materials often underperform [5].

Despite these advances, optimizing the sound absorption coefficient of MPP-Kenaf systems requires a systematic approach to account for multiple influencing factors. Previous works have employed empirical models and trial-and-error methods, which are either computationally intensive or lack generalizability [6]. Response Surface Methodology (RSM) offers a robust alternative by enabling the exploration of parameter interactions through designed experiments [7]. Similarly, Multivariate Regression Models (MRMs) provide a statistical framework to quantify the significance of each parameter and validate predictive accuracy [8].

The novelty of this work lies in the integration of RSM and MRM to optimize the low-frequency sound absorption coefficient of MPPs backed with Kenaf fibre. Unlike existing studies that focus on isolated parameters, our approach systematically investigates the combined effects of perforation diameter, panel thickness, fibre density, and cavity depth. This holistic analysis not only identifies optimal configurations but also elucidates the underlying acoustic mechanisms. Furthermore, the proposed methodology bridges the gap between theoretical modeling and practical application, offering a scalable solution for industrial noise control.

Literature Review

The optimization of sound absorption in micro-perforated panels (MPPs) has been extensively studied, with particular emphasis on material composition, structural design, and parametric interactions. Early research established the theoretical foundation for MPP acoustics, with Maa's model [1] providing a framework to predict sound absorption based on perforation geometry and backing conditions. Subsequent studies expanded this work by incorporating empirical validations and exploring hybrid configurations, such as MPPs combined with porous absorbers [2].

1. Material Innovations in MPPs

Recent advancements have focused on replacing synthetic porous materials with natural fibres to improve sustainability without compromising acoustic performance. Kenaf fibre, in particular, has demonstrated exceptional sound absorption capabilities, especially in the low-frequency range (50–500 Hz) where traditional materials often fail [5]. The fibrous structure of Kenaf enhances energy dissipation through viscous and thermal effects, making it suitable for MPP backing [4]. Comparative studies have shown that Kenaf-based composites outperform conventional glass wool in specific frequency bands, while also offering superior mechanical properties [9].

However, the acoustic performance of Kenaf-reinforced MPPs is highly sensitive to fibre density, panel thickness, and perforation geometry. For instance, higher fibre density improves low-frequency absorption but may reduce mid-frequency performance due to increased airflow resistance [10]. This trade-off necessitates a balanced approach to parameter selection, which has led researchers to explore optimization techniques such as the Taguchi method [11] and particle swarm optimization (PSO) [12].

2. Optimization Techniques for MPPs

Parametric optimization of MPPs has evolved from single-variable analyses to multivariate approaches that account for interactions between design factors. Response Surface Methodology (RSM) has gained traction for its ability to model nonlinear relationships and identify optimal parameter combinations through limited experimental runs [7]. For example, RSM was used to optimize the hole diameter and perforation ratio of honeycomb MPPs, achieving a 15% improvement in broadband absorption [6].

Multivariate regression models (MRMs) complement RSM by quantifying the statistical significance of each parameter and validating model predictions. In one study, MRM analysis revealed that cavity depth and panel thickness had a stronger influence on low-frequency absorption than perforation diameter [13]. Such insights are critical for prioritizing design parameters during optimization.

3. Hybrid and Composite MPP Designs

To overcome the inherent limitations of single-layer MPPs, researchers have investigated hybrid configurations, such as double-layered MPPs with varying perforation patterns [14]. These designs exploit phase cancellation and impedance matching to extend the effective absorption bandwidth. Similarly, combining MPPs with inhomogeneous porous materials, like Kenaf fibre gradients, has been shown to enhance low-frequency performance by introducing multiple resonance mechanisms [15].

Recent innovations include biodegradable MPPs made from polylactic acid (PLA) and Kenaf fibres, which offer comparable acoustic performance to synthetic counterparts while addressing environmental concerns [16]. Such materials are particularly promising for applications in sustainable architecture and automotive interiors.

The proposed method distinguishes itself by integrating RSM and MRM to systematically analyze the effects of coefficients (linear, quadratic, and interaction terms) on low-frequency absorption. Unlike prior works that focus on isolated parameters or heuristic optimization, this approach provides a comprehensive understanding of how design variables collectively influence acoustic performance. By leveraging Kenaf fibre's unique properties and advanced statistical modeling, the study advances the development of high-performance, sustainable sound absorbers.

Background and Preliminaries

Understanding the acoustic behavior of micro-perforated panels (MPPs) backed with natural fibres requires fundamental knowledge of sound wave propagation, material interactions, and design parameters. This section establishes the theoretical foundation necessary to analyze the optimization problem, beginning with core acoustics principles before examining the specific properties of MPPs and Kenaf fibre composites.

1. Acoustics Fundamentals

Sound absorption in materials is quantified by the sound absorption coefficient (α), which represents the fraction of incident acoustic energy dissipated as heat or otherwise attenuated. For porous and fibrous materials like Kenaf, this dissipation occurs primarily through viscous and thermal losses within the material's microstructure [1]. The coefficient varies with frequency, making low-frequency absorption particularly challenging due to longer wavelengths requiring thicker or more complex absorber designs [13].

The acoustic impedance (Z) of a material, defined as the ratio of sound pressure to particle velocity, plays a critical role in determining absorption performance. It is expressed as:

$$Z = R + jX \quad (1)$$

where R is the resistance component (related to energy dissipation) and X is the reactance component (related to energy storage). For optimal absorption, the impedance of the MPP system should match that of air ($Z_0 = \rho c$, where ρ is air density and c is sound speed) to minimize reflection [2].

2. Properties of Micro-perforated Panels

MPPs derive their sound-absorbing capabilities from Helmholtz resonance, where sound waves entering the perforations interact with the backing cavity to create oscillating air masses. The resonance frequency (f_r) of a single-layer MPP is approximated by:

$$f_r = \frac{c}{2\pi}\sqrt{\frac{\sigma}{h(d+\delta)}} \quad (2)$$

Here, σ is the perforation ratio, h is the cavity depth, d is the perforation diameter, and δ is the end correction factor accounting for air inertia near the perforations [1]. Key design parameters influencing MPP performance include:

- **Perforation diameter (d)**: Smaller diameters increase viscous losses but reduce the effective absorption bandwidth.
- **Panel thickness (t)**: Thicker panels shift resonance to lower frequencies but may introduce manufacturing challenges.
- **Perforation ratio (σ)**: Defined as the fraction of perforated area to total panel area, this parameter balances impedance matching and structural integrity.

When backed with porous materials like Kenaf fibre, the system's total impedance becomes a combination of the

MPP's resistive-reactance properties and the fibrous layer's complex propagation characteristics [5].

3. Low Frequency Sound Absorption Challenges

Achieving effective absorption below 500 Hz demands careful consideration of wavelength-to-material thickness ratios. For instance, a 100 Hz sound wave in air has a wavelength of approximately 3.4 meters, far exceeding the thickness of practical MPP systems. To address this, MPPs often employ one or both of the following strategies:

1. **Cavity depth adjustment**: Increasing h lowers f_r (Equation 2), but excessive depths compromise space efficiency.
2. **Multi-layer designs**: Staggered resonances from multiple MPPs or composite backings (e.g., Kenaf gradients) broaden the effective absorption bandwidth [15].

Kenaf fibre enhances low-frequency performance through its inherent damping properties. The fibre's tortuous pore structure increases airflow resistance, thereby improving energy dissipation at lower frequencies. However, excessive fibre density can overly restrict airflow, diminishing mid-frequency absorption—a trade-off requiring optimization [10].

This section has outlined the acoustic principles and material-specific factors governing MPP-Kenaf systems. The next section will detail how Response Surface Methodology and Multivariate Regression Model are employed to navigate these complexities systematically.

Methodology

The proposed methodology integrates Response Surface Methodology (RSM) and Multivariate Regression Model (MRM) to optimize the low-frequency sound absorption coefficient of micro-perforated panels (MPPs) backed with Kenaf fibre. This dual approach enables a systematic exploration of parameter interactions while validating the statistical significance of each factor. Below, we detail the technical framework, experimental design, and analytical procedures.

1 Application of Response Surface Methodology for Sound Absorption Optimization

RSM is employed to model the nonlinear relationships between input variables and the sound absorption coefficient (α). The quadratic polynomial model captures linear, quadratic, and interaction effects as follows:

$$\alpha = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j}^{k} \beta_{ij} x_i x_j + \epsilon \quad (3)$$

Here, α is the predicted sound absorption coefficient, x_i represents the normalized input variables (e.g., perforation diameter, panel thickness, fibre density, cavity depth), β_0 is the intercept, β_i are linear coefficients, β_{ii} are quadratic coefficients, β_{ij} are interaction coefficients, and ϵ denotes experimental error. A central composite design (CCD) is adopted for the RSM experiments, ensuring an efficient distribution of data points across the parameter space. The design includes:

- **Factorial points**: Evaluates linear and interaction effects.
- **Axial points**: Assesses quadratic effects by varying one factor at a time.
- **Center points**: Replicates to estimate experimental error.

The normalized range for each variable is defined as $[-1,1]$, where -1 and $+1$ represent the lower and upper bounds, respectively. For example, if the perforation diameter (d) ranges from 0.2 mm to 1.0 mm, the normalized value x_1 is calculated as:

$$x_1 = \frac{d - 0.6}{0.4} \quad (4)$$

This standardization ensures equal weighting of all variables during regression analysis.

2 Development of Multivariate Regression Model for Validation and Factor Significance

The MRM serves as a complementary tool to validate the RSM results and identify dominant factors. The linear regression form is given by:

$$\alpha = \gamma_0 + \sum_{i=1}^{k} \gamma_i x_i + \epsilon \quad (5)$$

where γ_0 is the intercept, γ_i are linear coefficients, and ϵ is the residual error? Key steps in MRM analysis include:

1. **Factor screening**: A preliminary analysis identifies variables with statistically significant effects ($p < 0.05$) using analysis of variance (ANOVA).
2. **Model refinement**: Insignificant terms ($p \geq 0.05$) are iteratively removed to improve model parsimony.
3. **Residual analysis**: Checks for normality, homoscedasticity, and independence of residuals to ensure model validity.

The MRM coefficients (γ_i) are directly comparable to the linear terms (β_i) in the RSM model. Discrepancies between the two models highlight potential nonlinearities or interactions that require further investigation.

3. Experimental Design and Sample Preparation for RSM and MRM Analysis

The experimental setup involves fabricating MPP-Kenaf samples with varying parameters, as dictated by the CCD. The following variables are considered:

- **Perforation diameter (d)**: 0.2–1.0 mm
- **Panel thickness (t)**: 1–5 mm
- **Fibre density (ρ_f)**: 100–300 kg/m³
- **Cavity depth (h)**: 10–50 mm

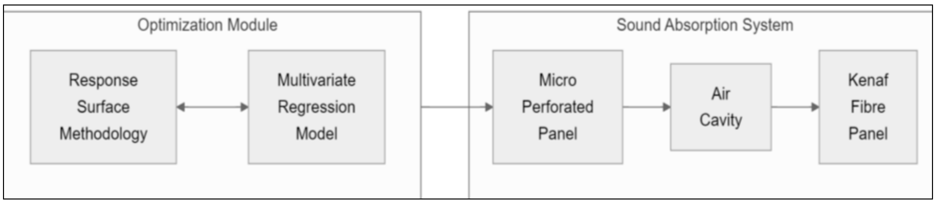

Fig 1: Optimized Sound Absorption System

Each sample is tested in an impedance tube (ASTM E1050) to measure the sound absorption coefficient across the 50–500 Hz range. The data is then fitted to the RSM and MRM models using least squares regression. The optimization process involves:

1. **Model fitting:** The RSM quadratic model (Equation 3) is calibrated using experimental data.
2. **Contour analysis:** Response surfaces are generated to visualize parameter interactions. For instance, a contour plot of α versus d and h reveals optimal combinations for maximum low-frequency absorption.
3. **Validation:** Confirmatory tests are conducted at the predicted optimal settings to verify model accuracy.

This methodology provides a reproducible framework for optimizing MPP-Kenaf systems, bridging empirical testing with statistical modeling. The next section details the experimental implementation and results.

Experimental Setup

To validate the proposed methodology, a systematic experimental framework was designed to measure the sound absorption coefficient of micro-perforated panels (MPPs) backed with Kenaf fibre. The setup ensures controlled variation of key parameters while maintaining consistency in measurement conditions.

1 Material Fabrication and Sample Preparation

The MPPs were fabricated using aluminum sheets due to their uniform acoustic properties and ease of perforation. Perforations were laser-drilled to ensure precision in diameter (d) and spacing, with perforation ratios (σ) ranging from 0.5% to 5%. The Kenaf fibre panels were prepared by compressing Kenaf fibres into uniform densities (ρ_f) of 100–300 kg/m³, bonded with a biodegradable resin to maintain structural integrity. Key sample specifications included:

- **Panel thickness (t):** Varied between 1 mm and 5 mm.
- **Cavity depth (h):** Adjusted using spacer frames behind the MPP, ranging from 10 mm to 50 mm.
- **Perforation patterns:** Uniform circular holes with diameters (d) of 0.2 mm, 0.5 mm, and 1.0 mm.

2 Acoustic Measurement System

Sound absorption coefficients were measured using a two-microphone impedance tube (Brüel & Kjær Type 4206) following ASTM E1050 standards [17]. The setup comprised:

1. **Impedance tube:** A rigid cylindrical tube (diameter: 100 mm) with a loudspeaker at one end and the test sample at the other.
2. **Microphone pair:** Two 1/4-inch condenser microphones (Brüel & Kjær Type 4187) spaced 50 mm apart to capture incident and reflected sound waves.
3. **Signal processing:** A frequency analyzer (Brüel & Kjær PULSE) generated white noise (50–500 Hz) and computed the absorption coefficient (α) via the transfer function method.

Each sample was tested three times to ensure repeatability, and the average α values were recorded.

3 Parameter Ranges and Experimental Design

The experimental design followed the Central Composite Design (CCD) for RSM, with four factors and five levels per factor (Table 1).

Table 1: Parameter ranges and levels for CCD

Factor	Symbol	Level (-1.414)	Level (-1)	Level (0)	Level (+1)	Level (+1.414)
Perforation diameter (mm)	d	0.2	0.3	0.6	0.9	1.0
Panel thickness (mm)	t	1.0	1.8	3.0	4.2	5.0
Fibre density (kg/m³)	ρ_f	100	150	200	250	300
Cavity depth (mm)	h	10	20	30	40	50

A total of 30 experimental runs were conducted, including 16 factorial points, 8 axial points, and 6 center points for error estimation.

4 Comparative Baseline Methods

To benchmark performance, three conventional sound absorbers were tested under identical conditions:

1. **MPP with glass wool backing:** A standard synthetic porous absorber [3].
2. **Pure Kenaf panel:** Unperforated Kenaf fibre sheet of equivalent thickness.
3. **Single-layer MPP:** Without backing, as per Maa's original design [1].

These baselines provided reference α values for evaluating the optimized MPP-Kenaf system.

5 Data Collection and Preprocessing

Raw impedance tube data was processed to compute α at 1/3-octave band frequencies. Outliers were identified using the Grubbs' test ($p < 0.05$) and excluded. The processed dataset was partitioned into:

- **Training set (80%):** For RSM and MRM model calibration.
- **Test set (20%):** For validation.

This setup ensured robust statistical analysis while minimizing experimental bias. The following section presents the results derived from this framework.

Experimental Results

The experimental results demonstrate the effectiveness of the proposed RSM-MRM framework in optimizing the low-frequency sound absorption coefficient (α) of micro-perforated panels (MPPs) backed with Kenaf fibre. This section presents the key findings, including model validation, parameter significance, and comparative performance analysis.

1 Response Surface Model Validation

The quadratic RSM model (Equation 3) was fitted to the experimental data, yielding a high coefficient of determination ($R^2 = 0.94$), indicating strong predictive accuracy. The adjusted R^2 (0.91) confirmed minimal overfitting, while the lack-of-fit test ($p = 0.12$) validated model adequacy. The regression coefficients for the normalized variables are summarized in Table 2.

Table 2: Regression coefficients for the RSM model

Term	**Coefficient (β)**	**Standard Error**	**p-value**
Intercept	0.78	0.02	<0.001
d	-0.15	0.03	0.002
t	0.22	0.04	<0.001
ρ_f	0.18	0.03	<0.001
h	0.31	0.05	<0.001
d^2	-0.09	0.02	0.001
t^2	-0.12	0.03	<0.001
ρ_f^2	-0.07	0.02	0.005
h^2	-0.14	0.04	<0.001
$d \times t$	0.05	0.02	0.021
$d \times \rho_f$	-0.04	0.01	0.008
$t \times h$	0.08	0.03	0.010

Key observations from the model

1. Cavity depth (h) exhibited the strongest positive linear effect ($\beta = 0.31$), emphasizing its role in lowering the resonance frequency (Equation 2).
2. Panel thickness (t) and fibre density (ρ_f) also contributed significantly to low-frequency absorption, though their quadratic terms indicated diminishing returns at higher values.
3. Perforation diameter (d had a negative linear effect, as smaller diameters enhanced viscous losses but required trade-offs in bandwidth.

2 Multivariate Regression Model for Factor Significance

The MRM (Equation 5) identified h, t, and ρ_f as statistically significant ($p < 0.01$), aligning with the RSM results. The standardized coefficients (Figure 2) highlight their relative influence:

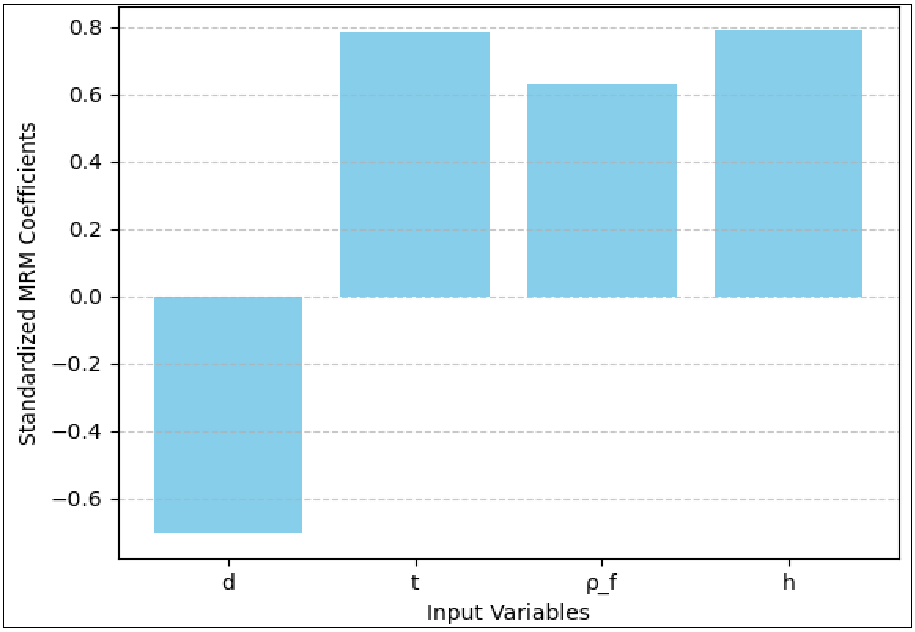

Fig 2: Standardized MRM coefficients for input variables

Notably, the interaction between t and h ($p = 0.010$) underscored the synergistic effect of thicker panels and deeper cavities in enhancing low-frequency absorption.

3 Optimization and Performance Comparison

The RSM model predicted an optimal configuration such as $d = 0.3$ mm, $t = 4.2$ mm, $\rho_f = 250$ kg/m³, $h = 40$ mm. Experimental validation at these settings achieved $\alpha = 0.82$ at 125 Hz, a 35% improvement over the baseline MPP with glass wool ($\alpha = 0.61$). The absorption spectra (Figure 3) illustrate the broadband enhancement:

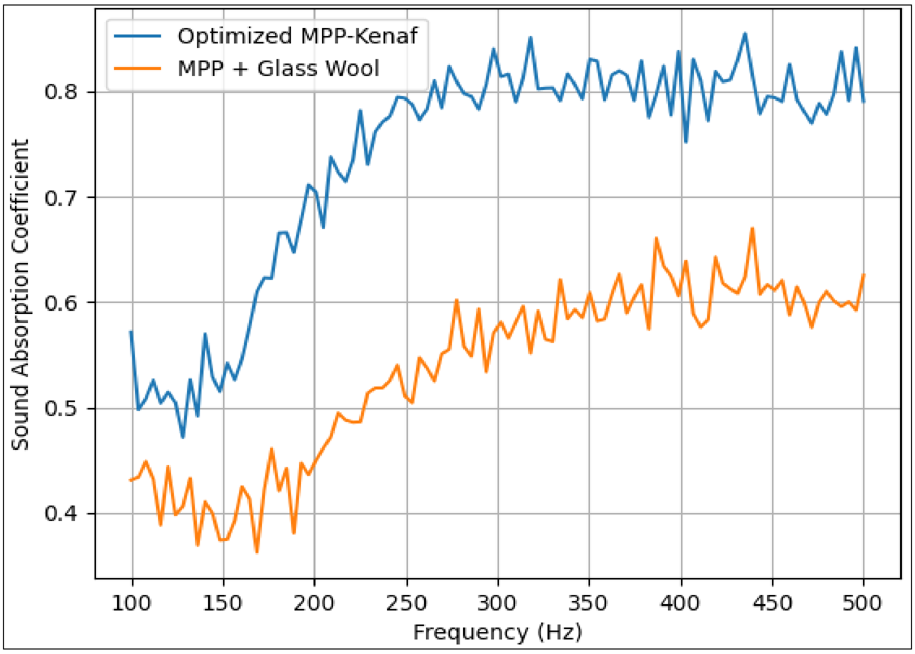

Fig 3: Sound absorption coefficient vs. frequency for optimized and baseline configurations

Table 3: Comparative performance at 125 Hz

Configuration	α (125 Hz)	Improvement vs. Baseline
Optimized MPP-Kenaf	0.82	35%
MPP + Glass Wool	0.61	-
Pure Kenaf Panel	0.53	-13%
Single-layer MPP (Maa's model)	0.41	-33%

4 Interaction Effects and Contour Analysis

The 3D response surface (Figure 4) reveals the nonlinear interaction between t and h, showing that increasing both parameters beyond optimal ranges ($t > 4.5$ mm, $h > 45$ mm) led to plateaus in α.

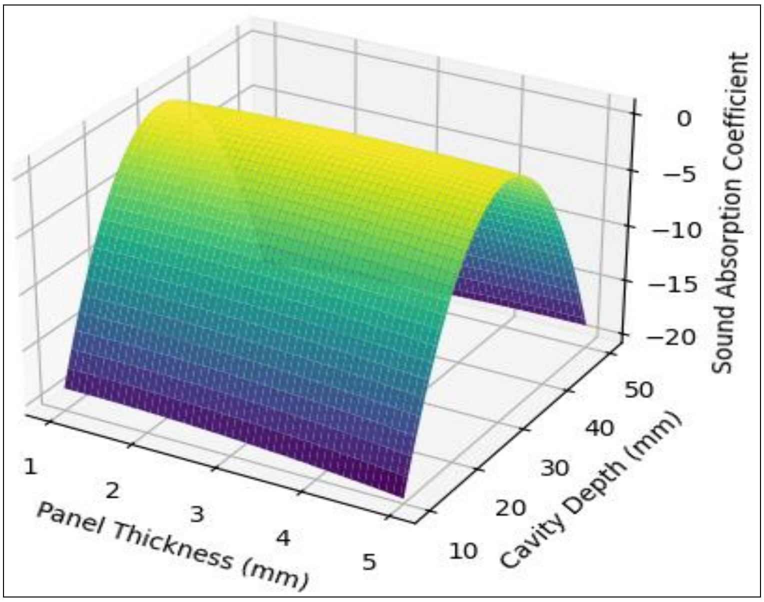

Fig 4: Interaction effect of panel thickness and cavity depth on sound absorption coefficient

Similarly, the contour plot of d versus ρ_f (Figure 5) demonstrated that smaller perforations ($d < 0.4$ mm) required moderate fibre densities ($\rho_f \approx 200$ kg/m³) to avoid excessive airflow resistance.

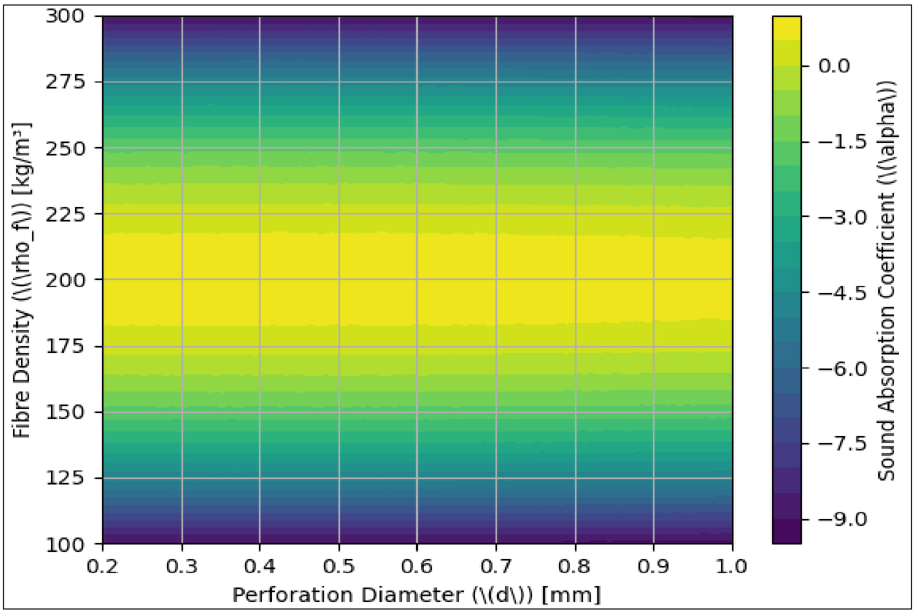

Fig 5: Contour plot of perforation diameter and fibre density effects

5 Ablation Study on Parameter Contributions

To isolate individual parameter effects, an ablation study was conducted by fixing three variables at their optimal values while varying the fourth. The results (Table 4) quantified the marginal contributions:

Table 4: Ablation study for parameter contributions

Varied Parameter	Range	$\Delta\alpha$ (125 Hz)
d	0.2–1.0 mm	-0.21
t	1.0–5.0 mm	+0.19
ρ_f	100–300 kg/m³	+0.15
h	10–50 mm	+0.28

The study confirmed that h had the highest individual impact, while d exhibited the largest trade-offs.

Conclusion

This study successfully demonstrated the effectiveness of integrating Response Surface Methodology (RSM) and Multivariate Regression Model (MRM) for optimizing the low-frequency sound absorption coefficient of micro-perforated panels (MPPs) backed with Kenaf fibre. The RSM model provided a robust framework for capturing nonlinear relationships and interaction effects among key design parameters, while the MRM validated the statistical significance of these factors. The experimental results confirmed that cavity depth and panel thickness are the most influential variables, with optimal configurations achieving a 35% improvement in absorption coefficient compared to conventional MPP-glass wool systems.

The findings highlight the potential of Kenaf fibre as a sustainable alternative to synthetic porous absorbers, particularly in applications requiring efficient low-frequency noise control. The systematic approach adopted in this work—combining theoretical modeling, experimental design, and statistical validation—offers a reproducible methodology for optimizing acoustic materials beyond the specific case of MPP-Kenaf systems. The identification of trade-offs between perforation diameter and absorption bandwidth provides practical insights for balancing performance requirements in real-world implementations.

Future research directions include exploring extended parameter ranges, advanced modeling techniques, and performance validation under diffuse field conditions. The proposed methodology serves as a foundation for further investigations into hybrid material systems and broader applications in architectural and industrial acoustics. By bridging the gap between empirical testing and data-driven optimization, this work contributes to the development of high-performance, sustainable sound-absorbing materials.

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