

ASSESSMENT OF NATURAL-FIBER CEILING MATERIALS FOR ROOM ACOUSTICS: COMSOL MULTIPHYSICS SIMULATION

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Abstract. Low-frequency indoor noise is difficult to control in small rooms because standing waves create strong spatial non-uniformity and resonance-driven peaks in sound pressure level (SPL). This study assessed sustainable porous ceiling treatments made from coconut fibre and sugarcane fibre using three-dimensional frequency-domain simulations in COMSOL Multiphysics (Pressure Acoustics). A 9 m × 3 m × 3 m furnished room was modelled with rigid walls and floor, while the ceiling was varied between a fully reflective default case and porous ceiling layers of 100, 200, 300, 400, and 500 mm for coconut fibre and sugarcane fibre porous. The porous ceilings were modelled using the Johnson–Champoux–Allard model, with material parameters taken from peer-reviewed sources and absorption coefficient data derived from impedance tube measurements of coconut fibre and sugarcane fibre composite specimens. Sound pressure level (SPL) was measured at receiver distances of 4.5 m and 9 m for standard 1/3-octave centre frequencies from 125 to 2000 Hz under source levels of 50, 70, and 90 dB. Both natural-fibre ceilings produced the largest SPL reductions in the mid and high bands, primarily by suppressing modal peaks around 1000–1250 Hz, while improvements at 125–250 Hz were smaller and more position dependent. Most of the frequency-averaged reduction was achieved at 20 cm thickness, with a smaller increase for thicker layers. The results support natural-fibre porous ceilings as practical, low-impact options for improving room acoustic conditions in the wave-dominated region and may be used as sustainable ceiling treatments for enhanced indoor acoustic comfort.

Keywords: room acoustics, porous ceiling, natural-fibre absorber, coconut fibre, sugarcane fibre, sound pressure level.

1. Introduction

Indoor noise remains a common environmental problem in houses, offices, public buildings, and schools. Noise enters from outdoors through façades, openings, and cracks, and from indoors through building services such as ventilation systems and pumps. Chronic exposure is linked with stress responses, sleep disruption, annoyance, and other health risks, and is therefore considered a public-health issue (Jarosińska et al., 2018).

A common indoor problem is low-frequency noise, which is poorly masked and propagates through building elements. It is linked to annoyance, sleep difficulties, and lower concentration, although the evidence base is smaller than for typical transport-noise metrics (Baliatas et al., 2016).

Small and medium rooms tend to associate low-frequency sound strongly with room modes, resulting in uneven spatial coverage, long decay at certain frequencies, and “boommy” bass that reduces perceived acoustic quality (Cecchi et al., 2018).

Many interior finishes offer minimal damping in the modal area. Mid and high frequencies are best suited to thin, porous materials, whereas low-frequency control typically requires thicker or tuned solutions and precise placement. This has led to increased interest in ceiling treatments as ceilings provide a large surface area and can be integrated with building constraints. There is also a growing need for low environmental impacts on petrochemical and mineral-based products, which has focused attention on natural fibres and agricultural residues as renewable, porous materials that lose sound through viscous and thermal losses (Berardi & Iannace, 2015).

Natural-fibre absorbers have been investigated as loose fills, felts, and bonded panels, with performance shaped by thickness, density, fibre morphology, and air flow resistivity. Coconut and sugarcane fibre are suitable residues, with studies showing improved absorption with increased thickness and suitable configurations such as air gaps, supporting their use as sustainable acoustic materials (Berardi & Iannace, 2015; Bhingare & Prakash,

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2021; Malawade & Jadhav, 2019; Mehrzad et al., 2022).

However, low-frequency room effects are not well captured by impedance-tube and reverberation-room tests due to the modal behaviour, which is spatial and three-dimensional. Wave-based numerical methods, especially finite element modelling, are therefore useful to investigate treatment-induced changes in pressure profiles, power flow, and stored acoustic energy in bounded rooms where geometrical acoustics is not reliable (Savioja & Svensson, 2019).

Johnson–Champoux–Allard (JCA) equivalent-fluid porous media models, referred to as the JCA/JCAL model family, link a small set of microstructural parameters (such as porosity, flow resistivity, tortuosity, and characteristic lengths) to frequency-dependent effective density and bulk modulus (Han et al., 2026). This enables phase-aware prediction of viscous and thermal losses in porous absorbers, and recent FEM studies show that careful parameterisation can reproduce measured room responses (Baliatsas et al., 2016; Kraxberger et al., 2023; Berardi & Iannace, 2015).

This study aims to quantify how sustainable porous ceiling treatments made from coconut fibre and sugarcane fibre change the room sound field in the wave-dominated region. Using three-dimensional frequency-domain FEM in COMSOL, (i) compare a fully reflective reference room with porous ceilings of 100–500 mm thickness, (ii) evaluate SPL changes at two receiver locations (4.5 m and 9 m from the source direction) at standard 1/3-octave centre frequencies from 125 to 2000 Hz, and (iii) assess thickness efficiency and material-to-material differences. The results are interpreted in terms of modal-peak suppression and spatial variability, and the implications for perceived sound are briefly discussed.

2. Methodology

Software and study design

The room acoustics were simulated in COMSOL Multiphysics (Pressure Acoustics, Frequency Domain, 3D) using the default model and two identical models except for the ceiling absorber definition with different thicknesses: coconut fibre case and sugarcane fibre case. All geometric settings, source settings, non-ceiling boundary conditions, mesh strategy, frequency list, and post-processing were kept constant to suppress the ceiling absorber effect.

Geometry

In this study, a room with dimensions length 9 meters, width 3 meters, and height 3 meters was modelled in SolidWorks. The room was full of a flat screen TV, a couch, a sideboard, a table, and 2 speakers. The sound source (speakers) was placed next to the TV Shown in Figure 1. The modelled build in SolidWorks was imported into COMSOL Multiphysics.

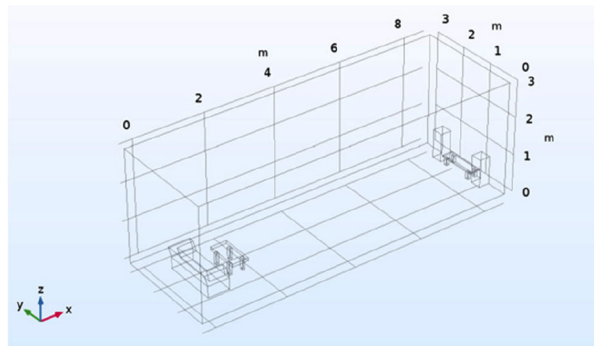


Figure 1. Room geometry with furniture, loudspeaker locations, and receiver points (R1 at 4.5 m and R2 at 9 m from the source direction). Receiver coordinates are given in the text

Physics and governing equation

The linear frequency-domain pressure acoustics formulation was applied to the air domain. The dependent variable is the complex acoustic pressure $p(f, x)$. At each frequency f , the acoustic response was computed under steady harmonic conditions. Air properties used in the models: Density $\rho_0 = 1.21 \text{ kg/m}^3$, Speed of sound $c_0 = 343 \text{ m/s}$.

Boundary conditions

Walls and floor: The model assumed acoustically rigid boundaries along walls and floor (sound-hard condition), with completely reflective materials. This focused the model concentration on the absorption properties of the ceiling.

Ceiling absorber (porous case): The ceiling was modelled as a porous absorber layer with thicknesses $t = 100, 200, 300, 400$ and 500 mm for each ceiling type (sugarcane and coconut fibre). A Johnson-Champoux-Allard (JCA) equivalent-fluid description of the porous domain was used. Ceiling material inputs (Table 1) were obtained from the literature source employed in this work (Fellah et al., 2005). Normal-incidence absorption coefficients derived from impedance-tube measurements (Figure 3) were fitted as a smooth fitted function of frequency in COMSOL to allow interpolation within the measured range and to avoid extrapolation beyond 125–2000 Hz. Notably, all SPL comparisons reported here are performed at 1/3-octave centre frequencies of the underlying absorption dataset, and the fitted function is used for model input convenience rather than to provide additional frequency resolution.

Acoustic pressure (sound sources)

Two loudspeakers were placed next to the TV, facing into the room, and were treated as harmonic acoustic point sources. Each source was prescribed a pressure amplitude corresponding to 50, 70, and 90 dB SPL in air, using the standard reference pressure $p_{\text{ref}} = 20 \text{ }\mu\text{Pa}$. The three

source levels were included to show that, under the linear pressure-acoustics formulation, spectral trends and relative reductions are independent of overall level (the field scales with source amplitude), while still reporting results at sound levels that are familiar in practice. The same source positions and amplitudes were used for all ceiling thicknesses and both fibre types.

$$L_p = 20 \log_{10} \left(\frac{P_{src}}{P_{ref}} \right). \quad (1)$$

In both ceiling cases, both sources were used at the same positions and amplitudes (International Organization for Standardization, 2003). Figure 2 shows the point pressure sources highlighted in blue dots.

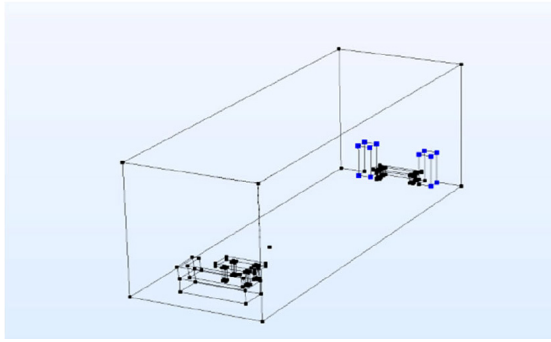


Figure 2. Locations of the two-point pressure sources (shown as blue point markers at the speaker positions). In COMSOL, point sources are attached to geometric vertices or points, which can appear similar to geometry junctions in the CAD model

Frequency-domain study

The average normal-incidence sound absorption coefficient of the coconut and sugarcane fibre materials is shown in Figure 3. These measured absorption data were used to obtain the absorption-coefficient relationship implemented in the COMSOL simulations. The steady-state acoustic response of the room under harmonic conditions was evaluated by a frequency-domain analysis. The study was implemented using the Pressure Acoustics, Frequency Domain solver, which computes

Table 1. Johnson–Champoux–Allard (JCA) input parameters used for the porous ceiling materials

Properties	Units	Coconut fibre	Sugarcane fibre
Porosity	—	0.93	0.95
Flow resistivity	Pa-s/m ²	8000	8000
Thermal characteristic length	m	0.0003	0.00035
Viscous characteristic length	m	0.00015	0.00018
Tortuosity factor	—	1.2	1.2
Static thermal permeability	m ²	0.000000003	0.0000000035

the acoustic pressure field $p(x, f)$ at each prescribed frequency f . For each frequency, the solution represents the magnitude and phase of the pressure response once transient effects are neglected, which is suitable for identifying low-frequency room modes and comparing absorber performance under controlled conditions (Patil & Kurbet, 2020). The simulation was conducted as a discrete frequency sweep over 13 frequency points at 1/3 octave covering the low-frequency range of interest:

$$f = \{125 - 2000\} \text{ Hz}. \quad (2)$$

This is equivalent to a sweep of 125 to 2000 Hz at standard 1/3-octave band center frequencies. Results were directly compared at each frequency with the same frequency list used for both material cases (coconut fibre and sugarcane fibre ceiling). COMSOL solved the governing frequency-domain acoustic under given boundary conditions and source definition at each frequency point and extracted the following quantities for analysis of receiver sound pressure level, and spatial pressure distribution for modal pattern visualization and evaluation of the ceiling absorber effect on low-frequency.

Mesh

The air domain was covered by a tetrahedral mesh. A wavelength criterion based on the maximum simulated angular momentum was used to set mesh resolution f_{max} :

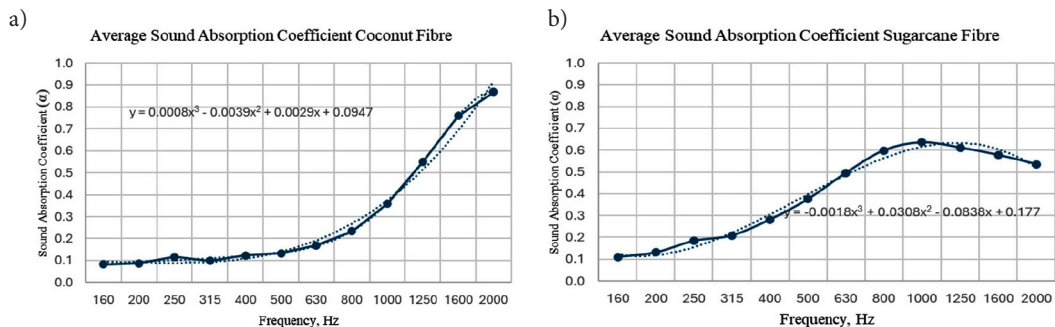


Figure 3. Average sound absorption coefficient for material across different frequency range: (a) – coconut fibre; (b) – sugarcane fibre

$$\lambda_{\min} = \frac{c_0}{f_{\max}}, \quad h_{\max} \leq \frac{\lambda_{\min}}{6};$$

$$\lambda_{\min} = \frac{343}{2000} = 0.1715 \text{ m};$$

$$h_{\max} \leq \frac{0.1715}{6} \leq 0.02858 \text{ m},$$
(3)

where λ_{\min} – the shortest wavelength in the simulation, which occurs at the highest frequency, f_{\max} – the highest frequency simulation in the frequency sweep (Hz), which is 2000 Hz, c_0 is the sound speed in air. This criterion guarantees at least six elements per wavelength at maximum frequency and affords sufficient sensitivity for frequency-domain pressure acoustics in enclosed environments.

Receiver-point evaluation

Receiver points (virtual microphones) were defined at two locations along the room length: R1 at 4.5 m and R2 at 9 m from the source direction. SPL was calculated from the pressure amplitude at each receiver point and frequency:

$$L_p(f) = 20 \log_{10} \left(\frac{|p(f)|}{p_{ref}} \right),$$
(4)

where $p_{ref} = 20 \mu\text{Pa}$.

Comparative metric

For each receiver and frequency, the difference between ceiling cases was computed as:

$$\Delta L_p(f) = L_{p,sugarcane}(f) - L_{p,coconut}(f).$$
(5)

Negative values show lower SPL in the sugarcane fibre ceiling case at the same position and frequency.

3. Result and discussion

Room Acoustics were modelled in COMSOL Multiphysics in the frequency domain through the Pressure acoustics interface. The room geometry, source setup, and wall and floor boundary conditions were kept constant while the porous ceiling parameters were varied to evaluate thickness-dependent absorption. Three cases were investigated: a fully reflective default room, coconut-fibre ceilings (100–500 mm), and sugarcane-fibre ceilings (100–500 mm) simulated at source levels of 50 dB, 70 dB, and 90 dB, respectively.

3.1. Sound pressure level at 50 dB Source (4.5 m and 9 m receiver points)

Coconut-fibre porous ceiling versus default room (SPL at 4.5 m and 9 m for 100–500 mm thickness)

At 9 m, the coconut-fibre ceiling reduces SPL across all 1/3-octave centre frequencies relative to the reflective room (Figure 4a), with mean reductions of 16 dB

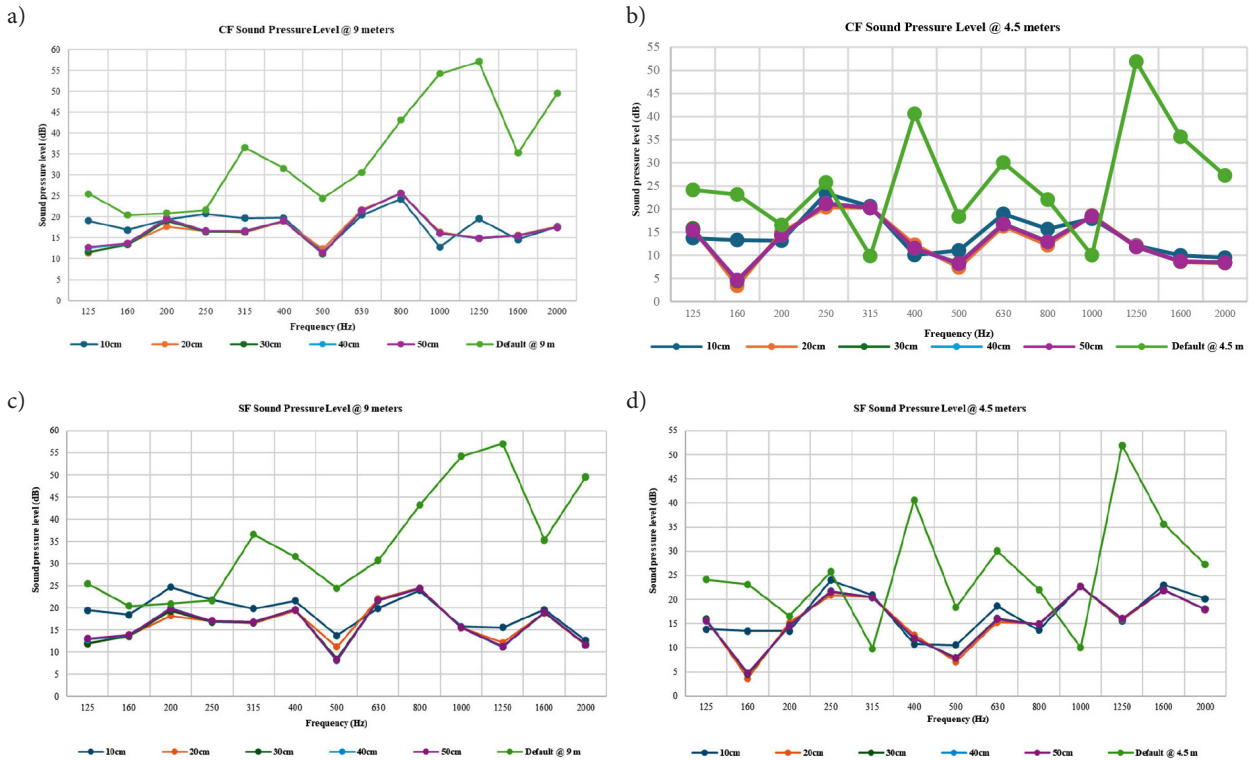


Figure 4. Sound pressure level at 50 dB source: (a) – coconut-fibre porous ceiling sound pressure level at 9 meters; (b) – coconut-fibre porous ceiling sound pressure level at 4.5 meters; (c) – sugarcane-fibre porous ceiling sound pressure level at 9 meters; (d) – sugarcane-fibre porous ceiling sound pressure level at 4.5 meters

(100 mm) and 18 dB (200–500 mm), suggesting that the maximum SPL reduction is at 200 mm; band means increase with frequency from 3 dB and 6–7 dB (125–250 Hz). Mean reductions are 11 dB (100 mm) and 12 dB (20–50 cm). At 4.5 m, mean reductions are 11 dB (100 mm) and 12 dB (200–500 mm) (Figure 4b), with band means of 6–8 dB, 9–10 dB, and 18–19 dB, and peak reductions at 1250 Hz (about 40 dB) and 400 Hz (28–30 dB), while local SPL increases occur at 315 Hz (about -10 dB) and 1000 Hz (about -7 to -8 dB).

Sugarcane-fibre porous ceiling versus default room (SPL at 4.5 m and 9 m for 10–50 cm thickness)

At 9 m, the sugarcane-fibre ceiling reduces SPL across most 1/3-octave centre frequencies (Figure 4c), with mean reductions of 15 dB (100 mm) and 18 dB (200–500 mm), and band means of about 1 dB and 7 dB (125–250 Hz), 13–15 dB (315–800 Hz), and 33–34 dB (1000–2000 Hz), with peak suppression strongest at 1250 Hz where SPL falls to 15 dB (100 mm) and 11–12 dB (200–500 mm) (about 41 dB and 45 dB reduction), while small increases occur for 100 mm at 200 Hz and 250 Hz. At 4.5 m, mean reductions are about 9 dB (100 mm) and 10 dB (200–500 mm), with band means of 6–8 dB, 9–10 dB, and about 11 dB, and peak reductions at 1250 Hz (about 36 dB) and 400 Hz (about 28–30 dB), while SPL increases persist at 315 Hz and 1000 Hz due to modal shifts.

3.2. Sound pressure level at 70 dB source (4.5 m and 9 m receiver points)

Coconut-fibre porous ceiling versus default room (SPL at 4.5 m and 9 m for 10–50 cm thickness)

At 9 m, the coconut-fibre ceiling reduces SPL relative to the reflective room (Figure 5a), with mean reductions of 16 dB (100 mm) and 18 dB (200–500 mm), showing that most SPL reduction is achieved by 200 mm; band means increase from 1.4 dB and 6–7 dB (125–250 Hz) to 14–15 dB (315–800 Hz) and about 33 dB (1000–2000 Hz), with peak suppression at 1250 Hz where the default 77 dB drops to 36 dB (100 mm) and 35 dB (200–500 mm), giving 41–42 dB reduction, and a small SPL increase only at 200 Hz for 100 mm (-3.27 dB). At 4.5 m (Figure 5b), mean reductions are 11 dB (100 mm) and 13 dB (200–500 mm), with band means of 7–9 dB, 9–10 dB, and about 19 dB, and strong peak reductions at 1250 Hz (about 40 dB) and 400 Hz (28–31 dB), while local SPL increases occur at 315 Hz (-11 dB) and 1000 Hz (-9 dB).

Sugarcane-fibre porous ceiling versus default room (SPL at 4.5 m and 9 m for 10–50 cm thickness)

At 9 m, the sugarcane-fibre ceiling reduces SPL (Figure 5c), with mean reductions of 16 dB (100 mm) and 19 dB (200–500 mm), band means of about 1 dB and 7 dB (125–250 Hz), 13–15 dB (315–800 Hz), and 33–35 dB (1000–2000 Hz), with peak suppression strongest at 1250 Hz where SPL falls to 15 dB (100 mm) and 11–12 dB (200–500 mm) (about 41 dB and 45 dB reduction), while small increases occur for 100 mm at 200 Hz and 250 Hz. At 4.5 m, mean reductions are about 9 dB (100 mm) and 10 dB (200–500 mm), with band means of 6–8 dB, 9–10 dB, and about 11 dB, and peak reductions at 1250 Hz (about 36 dB) and 400 Hz (about 28–30 dB), while SPL increases persist at 315 Hz and 1000 Hz due to modal shifts.

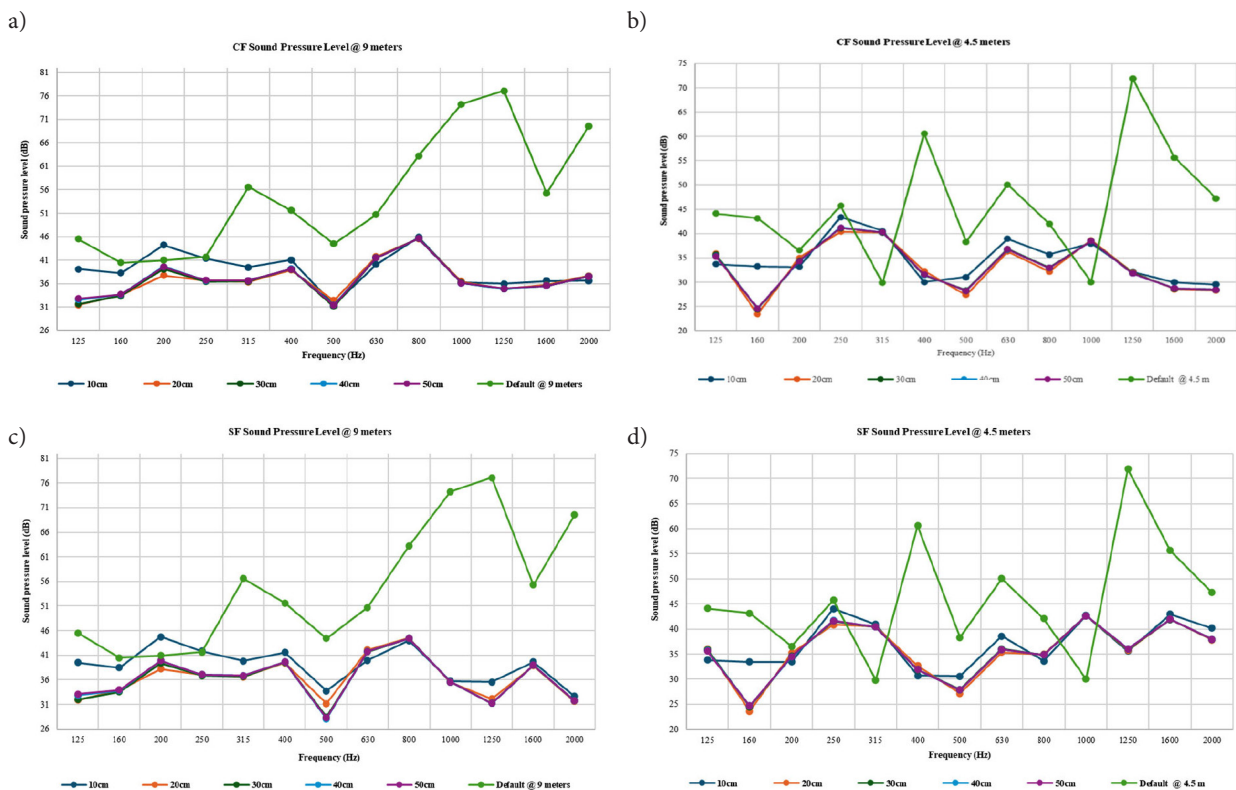


Figure 5. Sound pressure level at 70 dB source: (a) – coconut-fibre porous ceiling sound pressure level at 9 meters; (b) – coconut-fibre porous ceiling sound pressure level at 4.5 meters; (c) – sugarcane-fibre porous ceiling sound pressure level at 9 meters; (d) – sugarcane-fibre porous ceiling sound pressure level at 4.5 meters

(1000–2000 Hz), and peak suppression at 1250 Hz where the default 77 dB drops to 36 dB (100 mm) and 31 dB (200–500 mm), giving about 42 dB and 45–46 dB reduction, with small increases only for 100 mm at 200 Hz and 250 Hz. At 4.5 m (Figure 5d), mean reductions are about 9 dB (100 mm) and 10 dB (200–500 mm), with band means of 6–8 dB, 9–10 dB, and 11–12 dB, and peak reductions at 1250 Hz (about 36 dB) and 400 Hz (28–30 dB), while SPL increases persist at 315 Hz and 1000 Hz.

3.3. Sound pressure level at 90 dB source (4.5 m and 9 m receiver points)

Coconut-fibre porous ceiling versus default room (SPL at 4.5 m and 9 m for 10–50 cm thickness)

At 9 m, the coconut-fibre ceiling reduces SPL relative to the reflective room (Figure 6a), with mean reductions of 16 dB (100 mm) and 18 dB (200–500 mm), showing that most benefit is achieved by 200 mm; band means rise from 1.4 dB and 6–7 dB (125–250 Hz) to about 15 dB (315–800 Hz) and about 33 dB (1000–2000 Hz), with peak suppression at 1250 Hz where the default 97 dB drops to 56 dB (100 mm) and 55 dB (200–500 mm), giving about 41–43 dB reduction, and a small SPL increase only for 100 mm at 200 Hz (−3.27 dB). At 4.5 m (Figure 6b), mean reductions are 11 dB (100 mm) and 13 dB (200–500 mm), with band means of 7–9 dB, 9–10 dB, and about 19 dB, strong peak reductions at 1250 Hz (about 40 dB) and 400 Hz (28–31 dB), and local SPL

increases at 315 Hz (about −11 dB) and 1000 Hz (about −8 to −9 dB).

Sugarcane-fibre porous ceiling versus default room (SPL at 4.5 m and 9 m for 10–50 cm thickness)

At 9 m, the sugarcane-fibre ceiling reduces SPL (Figure 6c), with mean reductions of 16 dB (100 mm) and 19 dB (200–500 mm), band means of about 1 dB and 7 dB (125–250 Hz), 13–15 dB (315–800 Hz), and 33–34 dB (1000–2000 Hz), and peak suppression at 1250 Hz where the default 97.10 dB falls to 56 dB (100 cm) and 51–52 dB (200–500 mm), giving 42 dB and 45–46 dB reduction, with small increases only for 100 mm at 200 Hz and 250 Hz. At 4.5 m (Figure 6d), mean reductions are about 9 dB (100 mm) and 10 dB (200–500 mm), with band means of 6–8 dB, 9–10 dB, and 11–12 dB, peak reductions at 1250 Hz (about 36 dB) and 400 Hz (28–30 dB), and SPL increases persisting at 315 Hz and 1000 Hz.

These findings are in line with previous results for wave-based low-frequency room acoustics with porous treatments (Mondet et al., 2020) proposed a practical conversion from statistical absorption coefficients to provide better boundary conditions for phase-aware and time-domain simulations, which solves the common mismatch between available absorption data and the impedance data required by wave models. Pind et al. (2021) proposed an equivalent-fluid, extended-reaction scheme for porous layers, recognizing that local-reaction assumptions are

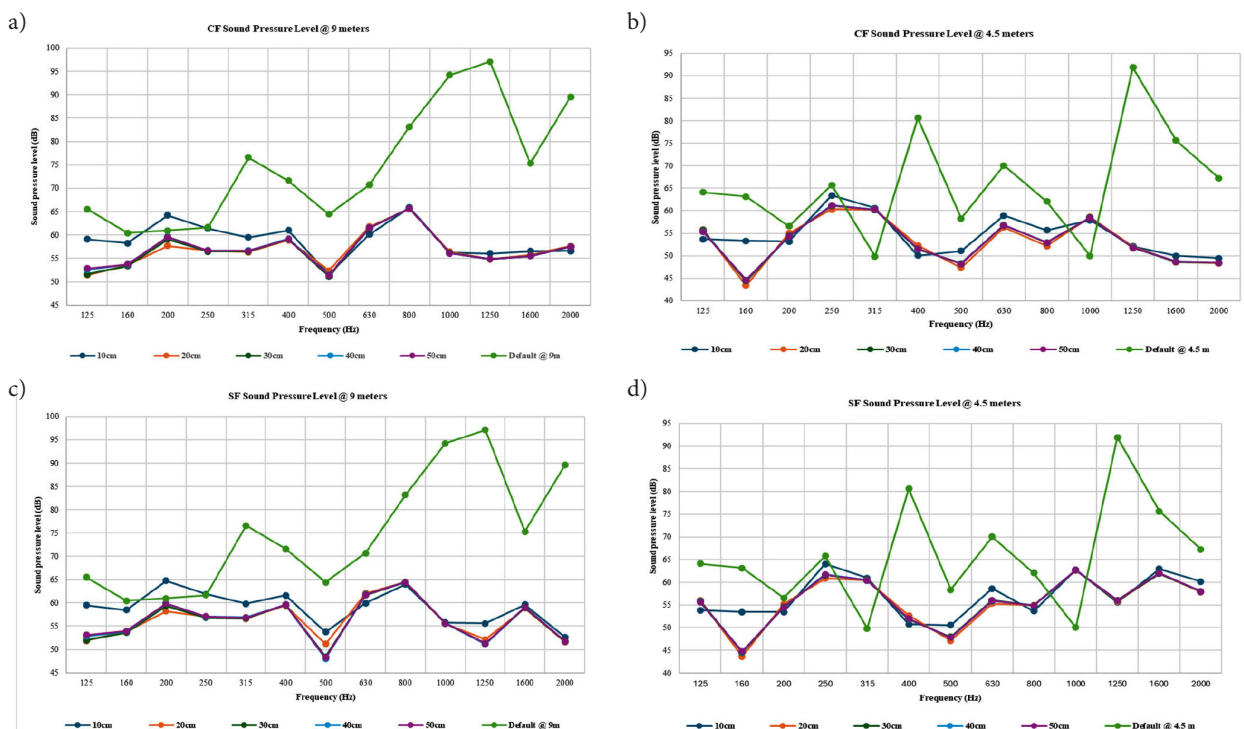


Figure 6. Sound pressure level at 90 dB source: (a) – coconut-fibre porous ceiling sound pressure level at 9 meters; (b) – coconut-fibre porous ceiling sound pressure level at 4.5 meters; (c) – sugarcane-fibre porous ceiling sound pressure level at 9 meters; (d) –sugarcane-fibre porous ceiling sound pressure level at 4.5 meters

not always adequate, particularly with backing or multi-layer effects, and that losses must be frequency dependent. Okuzono and Yoshida (2022) verified that porous and resonant absorbers can be treated in practical wave workflows at room scale and reported significantly higher computational efficiency for time-domain FEM than for frequency-domain FEM in 3D small-room cases, including porous-type absorbers. Wang and Hornikx (2023) stressed that robust boundary modelling is necessary for accurate prediction in the wave-dominated region by explicitly coupling porous layers, including thin coverings, to the room air domain.

Perceived sound quality: The large reductions reported at narrow-band modal peaks (for example near 1000–1250 Hz) indicate that the porous ceiling damped room resonances and reduced strong spectral irregularities at the receiver locations. This type of peak control is generally associated with reduced boominess and a more even response, rather than with a uniformly muffled sound. Nevertheless, porous ceilings can increase overall mid- and high-frequency absorption, which may shorten decay times and make a room sound drier. Because the present work is based on steady-state frequency-domain SPL at two points, it should be interpreted primarily as resonance and level control, not as a complete assessment of listening quality.

Sound quality metrics like STI, C50, EDT, or RT60 require an impulse-response (time domain) or a statistical / energy-based workflow with assumptions about source directivity and background noise. These were beyond the scope of the present FEM setup. Future work will therefore combine the porous-ceiling parameterisation used here with time-domain or hybrid room-acoustics simulations and in-room measurements to quantify both SPL smoothing and perceptual metrics.

4. Conclusions

The frequency-domain FEM results indicate that replacing a reflective ceiling with a porous natural-fibre layer can lower and smooth the room SPL spectrum. Across the 1/3-octave bands from 125 to 2000 Hz, both coconut- and sugarcane-fibre ceilings reduced the strength of resonance-driven peaks, with smaller and more position-dependent changes in the lowest bands (125–250 Hz). The relative reductions were consistent across the three source levels (50, 70, and 90 dB), as expected for a linear acoustic model.

Most of the frequency-averaged improvement was achieved at a porous thickness of about 200 mm, with diminishing returns for thicker layers up to 500 mm. At 9 m, both ceilings strongly reduced the dominant peaks around 1000–1250 Hz. At 4.5 m, the response was more sensitive to receiver position and included a few frequencies where SPL increased locally, consistent with treatment-induced shifts in nodal and antinodal regions.

Overall, the study supports natural-fibre porous ceilings as practical, low-impact options for resonance control in small rooms. For design practice in similar rooms, a 200 mm porous ceiling appears to be an efficient thickness, while thicker layers provide only modest additional benefit. Future work will validate these trends with in-room measurements, include spatial averaging over multiple receiver points, and refine porous boundary modelling using measured impedance or extended-reaction formulations, together with sound-quality metrics based on decay and intelligibility.

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