

Research Article

Natural Rubber Foam for Modular Acoustic Pods: Comparative Acoustic Performance and Full-Scale Prototype Performance Assessment

Natdanai Pratoom ^a and Nattapon Uthaipan ^{b,*}

^a Physical Systems and Environment Division, Prince of Songkla University, Songkhla 90110, Thailand.

^b Rubber Engineering Program, Department of Interdisciplinary Engineering, Faculty of Engineering, Prince of Songkla University, Songkhla 90110, Thailand.

ABSTRACT

Article history:

Received: 2026-06-21

Revised: 2026-08-02

Accepted: 2026-08-06

Keywords:

Natural rubber foam;
 Acoustic pod;
 Sound absorption coefficient;
 Sound transmission loss;
 Bio-based acoustic materials

This study investigated the acoustic performance of bio-based natural rubber foam (NR foam) relative to conventional acoustic materials for modular acoustic pod applications through laboratory-scale material screening and full-scale prototype performance assessment. The novelty of this work lies in the introduction of the proposed Normalized Acoustic Performance Index (NAPI), a study-specific composite metric developed to compare the balance between sound absorption and material-level sound transmission resistance, together with a system-level assessment of a full-scale acoustic pod incorporating NR foam. Five materials, including NR foam, polyester fiber, polyurethane (PU) foam, polystyrene (PS) foam, and coconut fiber, were evaluated using impedance tube methods for sound absorption coefficient (SAC) and sound transmission loss (STL). Among the five materials investigated and the selected normalization reference values, NR foam yielded the highest NAPI value of 0.58, indicating the most balanced combination of sound absorption and material-level sound transmission resistance among the tested specimens. A full-scale acoustic pod incorporating NR foam within the wall cavities was subsequently constructed and evaluated under field measurement conditions. The pod exhibited octave-band sound level differences ranging from 37.1 to 49.7 dB, with an arithmetic mean of 42.4 dB across 125–8000 Hz. These values represent the combined acoustic performance of the complete enclosure and do not isolate the individual contribution of the NR foam layer. The developed NR foam exhibited a bulk density of 0.4238 g/cm³, a compressive strength of 80 kPa, a flexible interconnected open-cell structure, and HBF classification under the horizontal burning test conditions employed. Overall, the findings demonstrate the potential of NR foam as a bio-based material providing a balanced combination of sound absorption and material-level sound transmission resistance for modular acoustic enclosure applications.

© 2026 Pratoom, N. and Uthaipan, N. Recent Science and Technology published by Rajamangala University of Technology Srivijaya

1. Introduction

The rapid expansion of open-plan offices, co-working spaces, and flexible learning environments has increased the demand for localized acoustic solutions that can provide both speech privacy and internal acoustic comfort without requiring permanent structural modifications (Jahncke, 2012; Haapakangas *et al.*, 2014; ISO 22955, 2021). Modular acoustic pods have emerged as a practical and scalable approach to meeting this need. However, effective acoustic pod design requires simultaneous control of two distinct mechanisms: sound insulation, which attenuates externally transmitted noise,

and sound absorption, which reduces internal reverberation and reflected sound energy (Kuttruff, 2016). Most commercially available acoustic materials perform well in only one of these functions: porous fibrous absorbers such as polyester fiber and polyurethane (PU) foam offer high sound absorption but poor insulation, while rigid closed-cell materials such as polystyrene (PS) foam provide effective insulation but limited absorption (Allard and Atalla, 2009; Kuttruff, 2016). Selecting a single material that fulfills both requirements simultaneously remains a key challenge in acoustic pod design.

* Corresponding author.

E-mail address: nattapon.u@psu.ac.th

Bio-based materials have attracted increasing interest as sustainable alternatives to conventional petroleum-derived acoustic products. Among these, natural rubber foam (NR foam), derived from renewable latex resources, exhibits an open-cell porous structure and inherent viscoelastic properties that may support dual-function acoustic performance. The acoustic performance of open-cell porous materials is governed primarily by pore structure, airflow resistance, and energy dissipation within the interconnected pore network (Allard and Atalla, 2009). In addition, the viscoelastic nature of natural rubber contributes to vibration damping and sound attenuation, enhancing its potential as a multifunctional acoustic material. Similar acoustic behavior has been reported for porous rubber-based and recycled foam materials (Maderuelo-Sanz *et al.*, 2012; Del Rey *et al.*, 2012; Dissanayake *et al.*, 2021; Neves de Alencar *et al.*, 2023). Flame-retardant additives can additionally improve its fire safety, increasing its suitability for indoor enclosure applications. Unlike conventional fibrous or closed-cell absorbers, which typically excel in only one acoustic function, the combination of an open-cell pore network with inherent viscoelastic damping is hypothesized to give NR foam a distinct advantage in achieving simultaneous sound absorption and sound insulation—a combination not readily achieved by the conventional acoustic materials evaluated in this study.

Although several studies have reported the sound absorption performance of rubber-based foams using impedance tube methods, such as Samaei *et al.* (2023) on kenaf-fiber-reinforced polyurethane foam, most investigations have focused on a single acoustic property (either sound absorption or sound transmission loss) without systematic comparison to conventional competing materials. Information regarding the combined sound absorption and sound insulation performance of NR foam relative to a range of alternative materials remains limited. Furthermore, the translation of material-level acoustic measurements to full-scale enclosure performance has rarely been validated experimentally (Asdrubali *et al.*, 2015; ISO 22955, 2021).

Therefore, this study aimed to systematically compare the sound absorption and sound insulation performance of NR foam against four conventional acoustic materials (polyurethane foam, polyester fiber, polystyrene foam, and coconut fiber) using standardized impedance tube methods. The material demonstrating the best overall acoustic performance was subsequently implemented in a full-scale modular acoustic pod prototype to validate its practical applicability under real operating conditions. Physical, mechanical, morphological, and flammability properties of the selected material were also characterized to assess its suitability for long-term indoor use.

2. Materials and Methods

2.1 Materials for comparative acoustic screening

Five sound-absorbing materials representing different structural categories were selected for comparative acoustic evaluation: natural rubber foam (NR foam), polyester fiber, polyurethane (PU) foam, polystyrene (PS) foam, and coconut fiber. NR foam represents a bio-based open-cell elastomeric foam; polyester fiber and coconut fiber represent fibrous absorbers; PU foam is a synthetic open-cell polymer foam; and PS foam is a closed-cell polymer foam commonly used for thermal insulation and sound barriers. The commercial materials evaluated in this study were sourced as follows: Polyester fiber was supplied by Top Insulation and Trading Co., Ltd., Bangkok, Thailand. PU foam was manufactured by Acoustic Surfaces Inc., USA. PS foam was manufactured by Polyfoam Manufacturing Co., Ltd., Bangkok, Thailand. Coconut fiber was manufactured by Victory Industrial Co., Ltd., Bangkok, Thailand.

2.2 Preparation of natural rubber foam

Natural rubber (NR) foam was prepared by mechanical foaming using the Dunlop process, followed by gelation and steam vulcanization. High-ammonia natural rubber latex, supplied by Chalong Latex Industry Co., Ltd., Thailand, with a dry rubber content (DRC) of 60.15% and a total solids content (TSC) of 61.63%, was used as the base material. Prior to compounding, the latex was stirred for 30 min to reduce the residual ammonia content. A potassium oleate solution was subsequently added to enhance latex stability and foaming efficiency.

All rubber compounding ingredients were commercially available and used as received. Zinc diethyldithiocarbamate (ZDEC), zinc 2-mercaptobenzothiazole (ZMBT), sulfur, calcium carbonate (CaCO_3), and Ional LC antioxidant were added to the latex and mixed overnight to obtain a homogeneous latex compound.

The compounded latex was then mechanically whipped according to the Dunlop process to generate a stable foam with an open-cell porous structure. Zinc oxide (ZnO) and diphenylguanidine (DPG) were subsequently incorporated as an activator and secondary accelerator, respectively. Expandable graphite, supplied by Qingdao Jintao Graphite Co., Ltd., China, was added as a flame-retardant agent to improve the fire resistance of the NR foam. Finally, sodium silicofluoride (SSF) was added as a gelling agent to stabilize the cellular structure and initiate gel formation. The resulting foam was poured into a rectangular stainless-steel mold and allowed to stand for 20 min to ensure complete gelation. The gelled foam was subsequently steam-vulcanized for 60 min.

After vulcanization, the foam was removed from the mold, thoroughly washed with distilled water to remove residual chemicals, and air-dried under ambient conditions, as illustrated in Figure 1. The formulation of the acoustic NR foam is summarized in Table 1.



Figure 1 Foaming process of open-cell natural rubber foam.

Table 1 Formulation of acoustic NR foam.

Ingredient	Quantities (phr)
60% High-ammonia NR latex	100
20% Potassium oleate solution	2
50% Sulfur dispersion	2.5
50% ZDEC dispersion	1
50% ZMBT dispersion	1
50% Ionol LC (antioxidant) dispersion	1
50% CaCO ₃	20
50% Flame retardant	10
30% DPG dispersion	1.5
50% ZnO dispersion	5.0
20% SSF dispersion	0.65

2.3 Sound absorption coefficient (Impedance tube)

The normal-incidence sound absorption coefficient of the tested materials was measured using an impedance tube according to ISO 10534-2. Circular specimens were cut to fit the internal diameter of the tube and mounted flush to minimize edge leakage and ensure accurate measurement. All materials were prepared at a uniform thickness of 40 mm prior to acoustic testing. The sound absorption performance of all five materials was evaluated over a frequency range of 250–5000 Hz. A thickness of 40 mm was selected to standardize specimen geometry for comparative screening and to correspond to the practical wall cavity depth used in the full-scale acoustic pod prototype (Section 2.6).

The noise reduction coefficient (NRC) was calculated as the arithmetic mean of the sound absorption coefficients at 250, 500, 1000, and 2000 Hz, which were selected to cover the main speech and office noise frequency range. Higher NRC values indicate better overall sound absorption performance.

2.4 Sound transmission loss (Impedance tube)

The sound transmission loss (STL) of the tested materials was measured using an impedance tube based on the transfer function method following ASTM E2611 and ISO 10534-2.

Circular specimens, each 40 mm thick, were fitted securely between the source and receiving sections of the tube to minimize edge leakage. Measurements were conducted over 250–5000 Hz. The average STL was calculated from the arithmetic mean of the values at 250, 500, 1000, and 2000 Hz. This value was used only for material comparison and was not converted to a sound transmission class (STC) rating.

2.5 Selection criteria for acoustic pod materials normalized acoustic performance index (NAPI)

The overall acoustic performance of the materials was evaluated using the normalized acoustic performance index (NAPI), calculated from the noise reduction coefficient and sound transmission loss according to Eq. (1):

$$NAPI = \sqrt{\frac{NRC}{NRC_0} \times \frac{\text{avg STL}}{STL_0}} \quad (1)$$

where NRC is the measured noise reduction coefficient of the tested material, and average STL is the measured average sound transmission loss (dB). Reference values of $NRC_0 = 0.90$ and $STL_0 = 35$ dB were selected to represent high-performance reference levels for normalization. These values were used solely for comparative screening within this study and should not be interpreted as standardized performance thresholds.

The geometric mean formulation was adopted to ensure that both acoustic properties contribute equally to the index and that poor performance in either property significantly reduces the overall NAPI score: a material with excellent absorption but negligible insulation, or vice versa, will yield a low NAPI despite being strong in one dimension. A NAPI value of 1.0 indicates that both selected reference values are simultaneously attained, whereas values greater than 1.0 may occur when both normalized acoustic properties exceed their respective reference values.

The proposed NAPI provides a single composite score for comparing the balance between sound absorption and material-level sound transmission resistance among the tested materials. It enables materials representing different structural categories, including porous absorbers, rigid insulators, and viscoelastic foams, to be compared on a common normalized scale. The index was developed solely as a study-specific screening tool and should not be interpreted as a standardized acoustic rating or as a universal acceptance criterion for acoustic pod wall construction.

2.6 Acoustic pod prototype

A full-scale modular acoustic pod (1.5 X 2.0 X 2.2 m) was constructed to evaluate natural rubber foam (NR foam) as a sound-absorbing material filled inside the 40 mm thick wall structure. The prototype consisted of a structural enclosure, an

acoustically sealed door, ventilation components, internal supporting panels, and wall cavities filled with NR foam shown in Figure 2.

The design was based on commercially available office pod systems used in workplaces, universities, hospitals, and co-working spaces, aiming to provide speech privacy and external noise reduction while maintaining ventilation and user comfort. Special attention was given to sealing joints, door interfaces, wall connections, and panel installation to minimize sound leakage and improve overall sound insulation performance. The prototype was used to validate laboratory-scale results under full-scale operating conditions.



Figure 2 Schematic design and full-scale prototype of the modular acoustic pod used for field sound insulation evaluation.

2.7 Field sound level difference measurement

The field sound insulation performance of the full-scale acoustic pod prototype was evaluated using a measurement procedure adapted from the general principles of ISO 16283-1. Broadband noise was generated by a loudspeaker positioned outside the acoustic pod to represent external environmental noise and typical sound disturbances encountered in office environments. Sound pressure levels were measured at designated positions outside and inside the enclosure.

Measurements were conducted over the frequency range of 125–8000 Hz to evaluate the acoustic performance of the enclosure in the low-, mid-, and high-frequency regions associated with environmental noise, speech, and mechanical equipment. Each measurement was repeated at least three times, and the mean values were reported.

The octave-band sound level difference (D_L), between the sound pressure levels measured outside (L_1) and inside (L_2) the acoustic pod was calculated using Eq. (2):

$$D_L = L_1 - L_2 \quad (2)$$

where (L_1) is the sound pressure level measured outside the acoustic pod (dB), and (L_2) is the corresponding sound pressure level measured inside the acoustic pod (dB).

A higher D_L value indicates a greater reduction in sound pressure level between the exterior and interior of the enclosure under specified measurement conditions. The measured sound level difference represents the overall field performance of the complete acoustic pod system, including the wall panels, NR foam-filled cavities, door, ventilation components, structural connections, and potential sound leakage through joints.

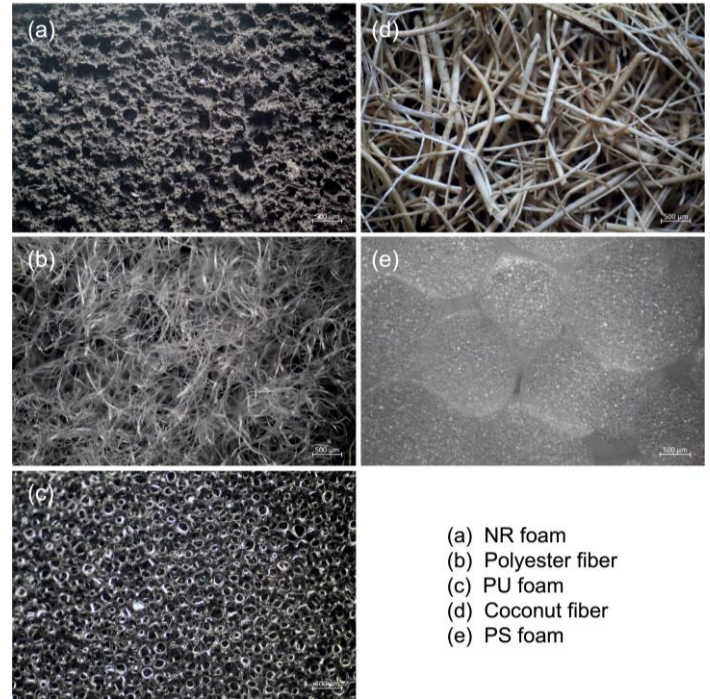


Figure 3 Optical microscope images of all five tested materials at 10x magnification.

2.8 Physical, mechanical, morphological, and flammability properties

Density was determined using an electronic density balance equipped with a hydrostatic weighing kit based on Archimedes' principle. Each specimen was weighed in air and in water. The bulk density (ρ_o) was measured using the specimen in its original, uncompressed state, whereas the apparent solid density (ρ_s) was determined after compressing the specimen at 500 psi to minimize the contribution of internal air voids. The apparent porosity was subsequently calculated using Eq. (3):

$$\text{Porosity (\%)} = \left(1 - \frac{\rho_o}{\rho_s}\right) \times 100 \quad (3)$$

Hardness was measured using a Shore OO durometer according to ASTM D2240. Compressive strength was evaluated following ASTM D3574 (adapted here in the absence of a current standard specific to natural rubber latex foam) at a crosshead speed of 50 mm/min. Morphology was examined using an optical microscope. Flammability was evaluated using the horizontal burning test specified in ISO 9772 by observing flame propagation, burning behavior, and self-extinguishing characteristics.

Table 2 Physical and structural characteristics of the five tested materials.

Material	Structure type	Density (g/cm ³)		Porosity (%)
		Bulk	Solid	
NR foam	Open-cell foam	0.4238 ± 0.0440	0.8036 ± 0.0226	47.3
Polyester fiber	Fibrous	0.0142 ± 0.0010	1.0659 ± 0.0452	98.7
PU foam	Open-cell foam	0.0239 ± 0.0014	0.7347 ± 0.0202	96.7
Coconut fiber	Fibrous	0.0745 ± 0.0079	0.8521 ± 0.0212	91.3
PS foam	Closed-cell foam	0.0117 ± 0.0007	0.0124 ± 0.0006	5.6

3. Results and Discussion

3.1 Physical and structural characteristics of sound-absorbing materials

Physical and structural characteristics of the five tested materials, namely natural rubber (NR) foam, polyester fiber, polyurethane (PU) foam, polystyrene (PS) foam, and coconut fiber, are summarized in Table 2. NR foam had the highest bulk density (0.4238 g/cm³) among all tested materials, substantially higher than the fibrous and synthetic foam alternatives (0.0117–0.0745 g/cm³). PS foam had the lowest bulk density (0.0117 g/cm³), reflecting its highly expanded closed-cell structure. The solid density of NR foam (0.8036 g/cm³) was comparable to that of other elastomeric and fibrous materials, indicating a dense rubber matrix despite the open-cell foam morphology. The high porosity of polyester fiber (98.7%) and PU foam (96.7%) reflects their loosely packed fibrous and open-cell structures, in which a large fraction of the material volume consists of interconnected air space. In contrast, NR foam exhibited a comparatively lower porosity (47.3%) together with a markedly higher bulk density, consistent with its denser rubber matrix. PS foam exhibited the lowest porosity (5.6%) among all tested materials, consistent with its closed-cell structure, in which the polymer matrix largely encloses discrete gas cells rather than forming an interconnected pore network. Representative optical micrographs of the five materials are shown in Figure 3. NR foam exhibits an irregular, interconnected open-cell structure, while polyester and coconut fibers form randomly oriented fibrous networks. PU foam shows relatively uniform open cells, whereas PS foam consists of large, closely packed closed cells separated by continuous cell walls, with no visible intercellular openings. This value should be interpreted with caution, as the compression-based method used to estimate apparent solid density may not fully collapse enclosed gas cells in closed-cell foams, and the true porosity of PS foam may be underestimated.

3.2 Comparative sound absorption performance

The sound absorption performance of polyester fiber, coconut fiber, PS foam, PU foam, and NR foam was evaluated using the impedance tube method. The SAC and NRC values are presented in Figure 4 and Table 3. At 250 Hz, NR foam exhibited the highest SAC (0.24), exceeding polyester fiber (0.17) and PU foam (0.14), indicating comparatively better low-

frequency absorption capability. However, at 1000–2000 Hz both polyester fiber and PU foam exceeded NR foam, with polyester fiber reaching 0.86 and PU foam reaching 0.68 at 2000 Hz, compared with 0.64 for NR foam. Consequently, NR foam's overall NRC (0.44) was equal to that of PU foam and lower than that of polyester fiber (0.54), despite NR foam's advantage at the lowest tested frequency. This behavior is consistent with the structural characteristics identified in Section 3.1: the high porosity of polyester fiber and PU foam favors efficient sound wave penetration into their loosely packed fibrous and open-cell structures, promoting relatively high mid-to high-frequency absorption, whereas the comparatively lower porosity and higher bulk density of NR foam restrict the free path available for sound wave propagation at these frequencies. In contrast, PS foam exhibited the lowest absorption performance (NRC = 0.07), with consistently low SACs (0.01–0.16) across the tested frequency range; its very low porosity and closed-cell structure (Section 3.1) prevent sound wave penetration almost entirely, limiting internal energy dissipation. Although NR foam did not achieve the highest NRC among the tested materials, its interconnected open-cell morphology and viscoelastic energy dissipation characteristics (Allard and Atalla, 2009; Asdrubali *et al.*, 2015) contribute to its moderate sound absorption capability.

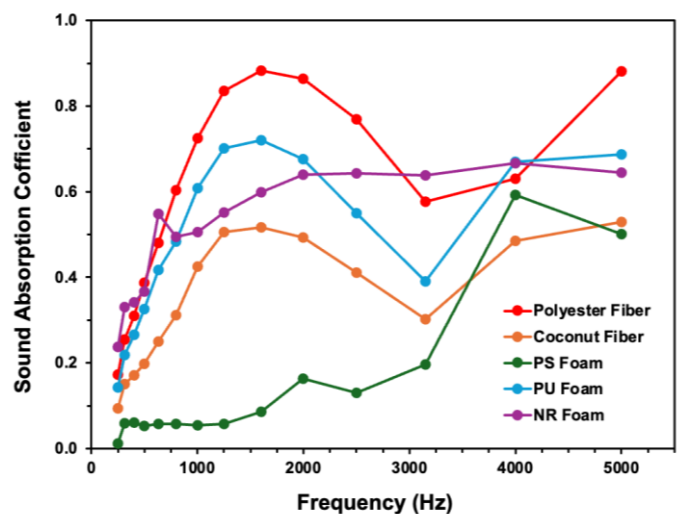


Figure 4 Sound absorption coefficient of different sound-absorbing materials measured using the impedance tube method.

3.3 Comparative sound insulation performance

The STL results of the five materials are presented in Figure 5 and Table 4. PS foam exhibited the highest average STL (39.35 dB), followed by NR foam (24.48 dB), polyester fiber (2.37 dB), PU foam (0.88 dB), and coconut fiber (0.63 dB). The high STL of PS foam is associated with its predominantly closed-cell structure, low pore connectivity, and continuous cell walls, which restrict sound transmission through the material. NR foam also showed substantially higher STL than the other porous materials. This finding is consistent with its comparatively higher bulk density and lower porosity, which restrict the free path available for sound wave transmission, combined with the viscoelastic nature of rubber, the higher mass density resulting from filler incorporation, and enhanced structural damping within the foam matrix. In contrast, the high porosity and low bulk density of polyester fiber and PU foam allow sound energy to pass through with minimal attenuation, consistent with their negligible STL values. Similar effects have been reported for porous rubber-based materials, where internal friction and viscoelastic damping improve resistance to sound transmission (Maderuelo-Sanz *et al.*, 2012; Del Rey *et al.*, 2012).

Notably, the NR foam exhibited a marked increase in STL at frequencies above 2000 Hz, indicating improved resistance to high-frequency sound transmission. This behavior is likely associated with the combined effects of frequency-dependent inertial resistance and energy dissipation within the porous viscoelastic structure. At higher frequencies, oscillatory airflow through the interconnected pores promotes viscous and thermal losses, while deformation of the flexible rubber cell walls contributes additional viscoelastic damping. Although the overall increase in STL is broadly consistent with the general tendency predicted by the mass law, the acoustic response of open-cell NR foam is poroelastic and therefore cannot be attributed to mass-law behavior alone (Allard and Atalla, 2009; Najib *et al.*, 2011).

3.4 Acoustic performance index for material selection

The proposed normalized acoustic performance index (NAPI), developed as a study-specific screening index, was calculated for all five tested materials using Eq. (1) to provide a single quantitative metric for comparing dual-function acoustic performance. Table 5 presents the NRC, average STL, and computed NAPI for each material, ranked in descending order of NAPI. The calculation normalizes both acoustic properties against the selected reference values ($NRC_0 = 0.90$; $STL_0 = 35$ dB) and applies the geometric mean to balance the contributions of sound absorption and sound insulation while penalizing poor performance in either dimension. These reference values were selected solely for comparative screening within this study and should not be interpreted as standardized performance thresholds. Building on the physical and structural

characteristics discussed in Section 3.1 and the individual absorption (Section 3.2) and insulation (Section 3.3) performance of each material, the NAPI combines both dimensions into a single comparative score.

Within the five materials investigated and the selected normalization references, NR foam yielded the highest NAPI value of 0.58, indicating the most balanced combination of sound absorption and material-level sound transmission resistance among the tested specimens. Although neither its NRC (0.44) nor its average STL (24.48 dB) was the highest individual value among all tested materials, their geometric combination produced the highest composite score. This result suggests that, under the experimental conditions and normalization approach employed, NR foam provided a more balanced dual-function acoustic response than the other materials evaluated.

PS foam ranked second with a NAPI of 0.30. Although PS foam achieved the highest average STL (39.35 dB), its very low NRC (0.07) substantially reduced its composite score through the geometric mean penalty, demonstrating that strong performance in only one acoustic dimension results in a lower composite score when both absorption and insulation are considered simultaneously. This result illustrates a key advantage of the NAPI formulation: a material that excels in insulation but fails in absorption, or vice versa, is penalized more severely than by a simple arithmetic average, reflecting the intended dual-function screening criterion used in this study. Notably, PS foam's average STL exceeds the selected reference value, STL_0 (35 dB), giving a normalized STL ratio above 1.0; even so, its very low NRC still dominates the geometric mean and keeps its overall NAPI low.

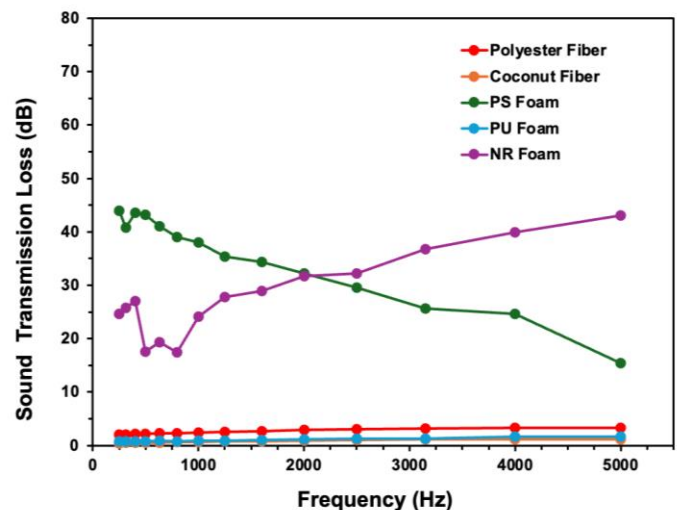


Figure 5 Sound transmission loss of different sound-absorbing materials measured using the impedance tube method.

Table 3 Sound absorption coefficient and NRC of different sound-absorbing materials.

Frequency (Hz)	Polyester Fiber	Coconut Fiber	PS Foam	PU Foam	NR Foam
250	0.17	0.09	0.01	0.14	0.24
500	0.39	0.20	0.05	0.33	0.37
1000	0.72	0.43	0.05	0.61	0.51
2000	0.86	0.49	0.16	0.68	0.64
NRC	0.54	0.30	0.07	0.44	0.44

Table 4 Sound transmission loss of different sound-absorbing materials.

Frequency (Hz)	Polyester Fiber	Coconut Fiber	PS Foam	PU Foam	NR Foam
250	1.96	0.43	43.95	0.73	24.58
500	2.19	0.54	43.17	0.81	17.56
1000	2.44	0.64	38.03	0.83	24.07
2000	2.88	0.91	32.23	1.15	31.70
Avg STL	2.37	0.63	39.35	0.88	24.48

Polyester fiber (NAPI = 0.20), PU foam (NAPI = 0.11), and coconut fiber (NAPI = 0.08) all ranked substantially lower, primarily due to their negligible STL values (2.37, 0.88, and 0.63 dB, respectively), which resulted in very small STL normalization ratios (0.068, 0.025, and 0.018). Despite their relatively good NRC performance (0.54, 0.44, and 0.30), the geometric mean was dominated by the low insulation contribution, producing NAPI values substantially lower than that of NR foam. These results indicate that, among the specimens and test conditions investigated, the polyester fiber, PU foam, and coconut fiber provided a less balanced combination of absorption and material-level sound transmission resistance than NR foam.

Overall, under the selected normalization reference values, the NAPI ranking was NR foam > PS foam > polyester fiber > PU foam > coconut fiber. This ranking applies specifically to the tested specimens, experimental conditions, and normalization approach employed in this study. The proposed NAPI should therefore be interpreted as a comparative screening tool rather than as a standardized acoustic rating or universal performance criterion.

Table 5 Proposed normalized acoustic performance index (NAPI) calculated using the selected reference values.

Material	NRC	Avg STL (dB)	NAPI
NR Foam	0.44	24.48	0.58
PS Foam	0.07	39.35	0.30
Polyester Fiber	0.54	2.37	0.20
PU Foam	0.44	0.88	0.11
Coconut Fiber	0.30	0.63	0.08

3.5 Physical and structural characteristics of NR foam

The physical, mechanical, morphological, and flammability properties of NR foam are summarized in Table 6. The foam exhibited a hardness of 35 ± 3 Shore OO, indicating a soft and flexible structure suitable for acoustic lining inside modular pod

walls. This softness improved vibration damping and enhanced sound energy dissipation within the porous structure.

Table 6 Physical, mechanical, morphological, and flammability properties of NR foam.

Properties	NR Foam
Hardness	35 ± 3 shore OO
Density	0.4238 ± 0.0440 g/cm ³
Compressive strength	80 ± 3 kPa
Flame resistance	HBF Class
Pore size	0.32 ± 0.12 mm

The density of NR foam was 0.4238 ± 0.0440 g/cm³, which is notably higher than conventional open-cell foam absorbers such as PU foam (0.0239 g/cm³) and polyester fiber (0.0142 g/cm³). This elevated density, combined with the interconnected open-cell pore network, contributes to enhanced resistance to airborne sound transmission through increased material mass, while the porous microstructure simultaneously enables sound energy dissipation through viscous friction and thermal conduction (Allard and Atalla, 2009; Maderuelo-Sanz *et al.*, 2012).

The compressive strength was 80 ± 3 kPa, indicating sufficient structural stability while maintaining elasticity and resilience. This property is particularly important for maintaining dimensional stability during long-term use and installation.

The flammability test classified the material as HBF (Horizontal Burning, self-extinguishing) according to ISO 9772, indicating low horizontal burning rate and self-extinguishing characteristics. These results confirm that the developed NR foam provides adequate fire safety for indoor acoustic enclosure applications.

The cellular morphology of NR foam showed an interconnected open-cell structure with an average pore size of 0.32 ± 0.12 mm (Figure 6). This porous network promotes sound-wave penetration and energy dissipation through viscous friction, thermal losses, and deformation of the flexible rubber cell walls. The observed increase in SAC with frequency is consistent with the behavior of porous

absorbers, as shorter-wavelength sound interacts more effectively with the pore network and produces greater internal energy dissipation at higher frequencies (Allard and Atalla, 2009; Del Rey *et al.*, 2012).

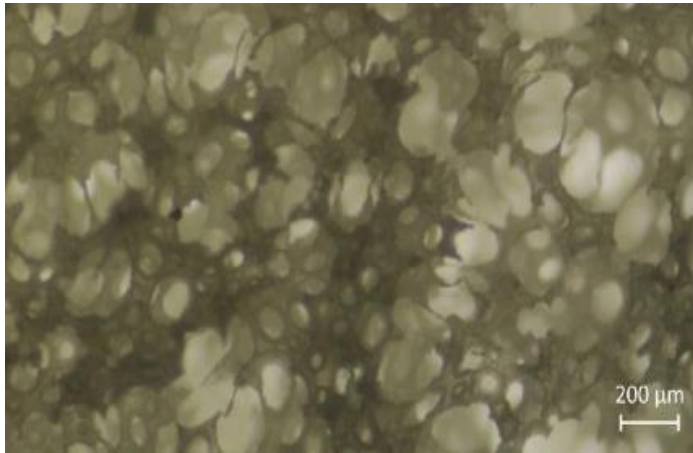


Figure 6 Open-cell porous morphology of a thin-section NR foam specimen observed under transmitted-light illumination using an optical microscope at 25X magnification.

3.6 Full-scale acoustic pod performance assessment

A full-scale acoustic pod prototype ($1.5 \times 2.0 \times 2.2$ m) was constructed using NR foam as the acoustic infill material within the wall cavities. The field sound insulation performance was evaluated by measuring octave-band sound level difference (D_L) over the frequency range of 125–8000 Hz, as shown in Table 7. The measured D_L values ranged from 37.1 to 49.7 dB, with a mean of 42.4 dB across the 125–8000 Hz range, demonstrating strong overall sound insulation performance suitable for practical acoustic enclosure applications. The measured D_L values varied across the investigated frequency range. The highest value, 49.7 ± 1.7 dB, was recorded at 125 Hz, indicating the greatest reduction in sound pressure level between the exterior and interior of the acoustic pod under the specified measurement conditions. The acoustic response at low frequencies is influenced by several interacting factors, including the mass and stiffness of the enclosure panels, structural vibration, cavity behavior, sealing conditions, source and receiver positions, and possible sound transmission through joints. Therefore, the high D_L value observed at 125 Hz should be interpreted as the response of the complete enclosure system and cannot be attributed solely to the NR foam layer.

Table 7 Field sound level difference (D_L) of the full-scale acoustic pod prototype.

Frequency (Hz)	D_L (dB)
125	49.7 ± 1.7
250	41.3 ± 0.4
500	40.8 ± 1.6
1000	37.1 ± 1.4
2000	48.8 ± 0.6
4000	40.8 ± 1.3
8000	38.2 ± 1.3

In the mid-frequency range of 250–1000 Hz, the D_L values decreased from 41.3 ± 0.4 to 37.1 ± 1.4 dB, with the lowest value occurring at 1000 Hz. This reduction may reflect the frequency-dependent response of the enclosure, including structural coupling between wall components, panel vibration, cavity effects, and sound transmission through joints, the door, or ventilation components. Resonance-related behavior may also have contributed to the observed reduction; however, the available measurements are insufficient to identify a specific resonance mechanism conclusively.

At 2000 Hz, D_L increased to 48.8 ± 0.6 dB. Because this frequency lies within a range relevant to speech communication, the result suggests that the enclosure can substantially reduce some speech-related frequency components under the test conditions employed. Nevertheless, speech privacy cannot be established from the sound level difference at a single frequency and would require additional evaluation using appropriate speech intelligibility or privacy metrics. At 4000 and 8000 Hz, the measured D_L values were 40.8 ± 1.3 and 38.2 ± 1.3 dB, respectively, indicating that measurable sound pressure level reduction was maintained across the investigated high-frequency region.

The arithmetic mean D_L across the measured octave bands was 42.4 dB. This value is reported only as a descriptive summary of the frequency-dependent results and should not be interpreted as a standardized single-number sound insulation rating. In addition, the measured mean should not be directly compared with criteria specified using different measurement procedures or acoustic descriptors. The standard deviations ranged from ± 0.4 to ± 1.7 dB, indicating relatively consistent repeated measurements under the same experimental conditions. The greater variation observed at 125 Hz may be associated with the sensitivity of low-frequency measurements to source and receiver positions, room boundaries, environmental conditions, and structural vibration.

Overall, the full-scale assessment demonstrated that the acoustic pod provided a sound level difference of at least 37.1 dB across the measured octave bands under the specified test conditions. NR foam was incorporated into the wall cavities because it exhibited a balanced combination of sound absorption and material-level sound transmission resistance during laboratory screening. However, the measured D_L values represent the combined performance of the complete enclosure, including the wall panels, NR foam-filled cavities, door, ventilation components, sealing details, and structural connections. Because a reference pod without NR foam and component-level measurements were not included, the individual contribution of NR foam to the full-scale sound level difference could not be quantitatively isolated. The results therefore provide a practical demonstration of the acoustic performance of a full-scale pod incorporating NR foam rather than direct validation of the material-level results.

3.7 Practical implications

The cost–performance relationship of the evaluated materials is illustrated in Figure 7. Although NR foam exhibited a slightly higher material cost than some conventional porous absorbers, it provided the highest overall dual-function acoustic performance, as reflected by the highest NAPI value among the tested materials under the selected normalization references.

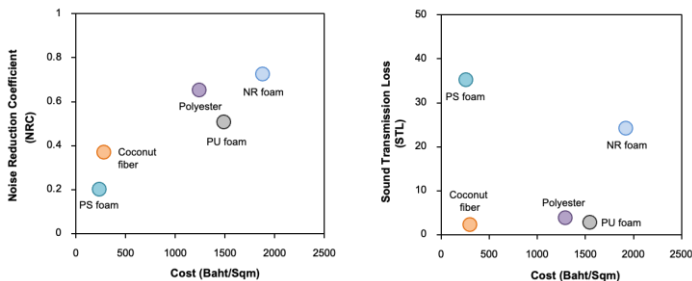


Figure 7 Cost–performance relationship of natural rubber foam and conventional acoustic materials for modular acoustic pod applications.

In contrast, polyester fiber and PU foam offered lower material costs but delivered lower overall acoustic performance due to their limited sound insulation capability. PS foam achieved excellent sound insulation performance; however, its low sound absorption reduced its suitability for enclosed acoustic environments where both functions are required simultaneously.

The balanced combination of sound absorption and sound insulation provided by NR foam enables the use of a single acoustic layer, reducing the need for additional absorptive or insulating materials. This simplifies panel construction and installation while potentially lowering overall system complexity. Furthermore, natural rubber is a renewable and domestically available resource, offering sustainability advantages and reducing dependence on imported petroleum-based materials. These characteristics make NR foam a promising material for modular acoustic pod applications, where acoustic effectiveness, structural simplicity, and long-term sustainability are important design considerations.

4. Conclusion

This study investigated the acoustic performance of bio-based NR foam through laboratory-scale comparison with conventional sound-absorbing materials and full-scale evaluation in a modular acoustic pod prototype. Among the five materials tested, NR foam achieved the highest overall dual-function acoustic performance (NAPI = 0.58), with a moderate NRC value of 0.44 (comparable to PU foam and below polyester fiber's 0.54) together with a substantially higher sound transmission loss of 24.48 dB. These findings indicate that NR foam can contribute to both sound absorption and sound insulation under the experimental conditions employed.

The full-scale acoustic pod prototype incorporating NR foam achieved sound level difference values ranging from 37.1 to 49.7 dB, with an average value of 42.4 dB over the frequency range of 125–8000 Hz. The observed performance at 125 and 2000 Hz suggests that the developed system has potential for reducing low-frequency and speech-related sound transmission in modular acoustic enclosures. Overall, the results demonstrate the potential of NR foam as an acoustic material for modular enclosure systems and provide an initial performance assessment progressing from material-scale screening to full-scale prototype testing.

5. Acknowledgments

The authors gratefully acknowledge financial support from Prince of Songkla University Science Park under the Technology to Industry Convergence Program (Grant No. PSUP4-2/68).

6. References

- Allard, J.F. and Atalla, N. 2009. **Propagation of Sound in Porous Media: Modelling Sound Absorbing Materials** (2nd ed.). John Wiley & Sons.
- Asdrubali, F., D'Alessandro, F. and Schiavoni, S. 2015. A review of unconventional sustainable building insulation materials. **Sustainable Materials and Technologies** 4: 1–17.
- ASTM D2240. 2021. Standard test method for rubber property—Durometer hardness. **ASTM International**.
- ASTM D3574. 2022. Standard test methods for flexible cellular materials—Slab, bonded, and molded urethane foams. **ASTM International**.
- ASTM E2611. 2019. Standard test method for normal incidence determination of porous material acoustical properties based on the transfer matrix method. **ASTM International**.
- Del Rey, R., Alba, J., Arenas, J.P. and Sanchis, V.J. 2012. An empirical modelling of porous sound absorbing materials made of recycled foam. **Applied Acoustics** 73(6–7): 604–609.
- Dissanayake, D.G.K., Weerasinghe, D.U., Thebuwanage, L.M. and Bandara, U.A.A.N. 2021. An environmentally friendly sound insulation material from post-industrial textile waste and natural rubber. **Journal of Building Engineering** 33: 101606.
- Haapakangas, A., Hongisto, V., Hyönä, J., Kokko, J. and Keränen, J. 2014. Effects of unattended speech on performance and subjective distraction: The role of acoustic design in open-plan offices. **Applied Acoustics** 86: 1–16.
- ISO 9772. 2020. Cellular plastics—Determination of horizontal burning characteristics of small specimens subjected to a small flame. **International Organization for Standardization**.

- ISO 10534-2. 2001. Acoustics—Determination of sound absorption coefficient and impedance in impedance tubes—Part 2: Transfer-function method. **International Organization for Standardization**.
- ISO 16283-1. 2014. Acoustics—Field measurement of sound insulation in buildings and of building elements—Part 1: Airborne sound insulation. **International Organization for Standardization**.
- ISO 22955. 2021. Acoustics—Acoustic quality of open office spaces. **International Organization for Standardization**.
- Jahncke, H. 2012. Open-plan office noise: The susceptibility and suitability of different cognitive tasks for work in the presence of irrelevant speech. **Noise and Health** 14(61): 315-320.
- Kuttruff, H. 2016. **Room Acoustics** (6th ed.). CRC Press.
- Maderuelo-Sanz, R., Nadal-Gisbert, A.V., Crespo-Amorós, J.E. and Parres-García, F. 2012. A novel sound absorber with recycled fibers coming from end-of-life tires (ELTs). **Applied Acoustics** 73(4): 402–408.
- Najib, N.N., Ariff, Z.M., Bakar, A.A. and Sipaut, C.S. 2011. Correlation between the acoustic and dynamic mechanical properties of natural rubber foam: Effect of foaming temperature. **Materials and Design** 32(2): 505–511.
- Neves de Alencar, L., Guedes Paiva, F.F., Okimoto, F.S., Boaventura Bacarin, G., Dognani, G., Salmazo, L.O., dos Santos, R.J., Camargo Cabrera, F. and Job, A.E. 2023. Natural rubber/wood composite foam: Thermal insulation and acoustic isolation materials for construction. **Cellular Polymers** 42(2): 55–72.
- Samaei, S.E., Berardi, U., Asilian Mahabadi, H., Soltani, P. and Taban, E. 2023. Optimization and modeling of the sound absorption behavior of polyurethane composite foams reinforced with kenaf fiber. **Applied Acoustics** 202: 109176.