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ORIGINAL ARTICLE

Tropical wood acoustics: impregnation effects on Cajuput, Mangium, and Mango woods for sustainable building materials

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Abstract

This study explores the acoustic properties of three tropical woods—Cajuput (*Melaleuca cajuputi*), Mangium (*Acacia mangium*), and Mango (*Mangifera indica*)—as sustainable materials for sound absorption. The wood samples were prepared in a standardized cylindrical shape, impregnated with zinc chloride ($ZnCl_2$), engine oil (EO), or coconut oil (CO), and subjected to heat treatment at 105 °C for 3 h. Acoustic analyses using an impedance tube revealed that CO treatment notably enhanced the Sound Absorption Average (SAA), with Cajuput wood showing a remarkable 53% improvement. Sound absorption performance varied across frequency ranges, with EO and CO treatments notably improving low, medium, and high-frequency bands in most woods, while $ZnCl_2$ exhibited less pronounced effects. However, all treatments reduced Sound Transmission Loss (STL), indicating a trade-off between sound absorption and insulation properties. Statistical analysis using two-way ANOVA confirmed the significant influence of wood type and treatment on acoustic performance across all parameters. These findings underscore the potential of tropical woods, particularly when treated with eco-friendly substance like coconut oil, as sustainable acoustic materials.

1 Introduction

Noise pollution, particularly from outdoor sources, has become a pressing concern in modern housing design. Excessive noise negatively affects the quality of life, making it essential to ensure a quiet and comfortable indoor environment. This necessitates a focus on the acoustic characteristics of building materials to effectively mitigate noise and create serene living spaces. As environmental concerns grow, the importance of sustainable building materials has come to the forefront (Fattahi et al. 2024; Halashi et al. 2024; Mohammadi et al. 2024). Acoustic materials that not only improve noise reduction but also align with sustainability goals are highly sought after (Shahrzad et al. 2022; Sukhawipat et al. 2022). The development of such materials addresses the dual challenge of enhancing living conditions while reducing environmental impact, thereby contributing to sustainable urban development (Mersal 2016; Van Oorschot et al. 2024).

Wood stands out as a naturally sustainable material with unique acoustic properties derived from its cellular structure (Jiang et al. 2004; Jang and Kang 2021, 2022a, b), enabling it to attenuate sound waves effectively. As a porous sound absorber, wood allows sound waves to penetrate its structure and dissipate energy, making it a promising candidate for acoustic applications. These properties can be further enhanced and optimized through treatments that alter its physical and chemical composition, adding versatility to its use in building interiors. However, existing research on acoustic building materials has largely focused on temperate species (Jang and Kang 2021, 2022b, c, d, e), leaving a significant gap in understanding the acoustic potential of tropical woods.

The porosity of a material plays a pivotal role in its ability to absorb sound (Chanlert et al. 2022b; Srisawas et al. 2024) especially in wood-type materials (Jang and Kang

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2022c, d). Higher porosity facilitates the entry of sound waves into the material, where they are dissipated through friction and other mechanisms (Allard and Atalla 2009). This makes porosity one of key parameters in the design of acoustic materials, particularly for wood-based solutions. However, porosity alone does not determine acoustic performance (Johnson et al. 1987; Champoux and Allard 1991). Flow resistivity, which measures the material's resistance to air movement, also significantly affects sound absorption (Delany and Bazley 1970). An optimal balance of porosity and flow resistivity is essential to achieve superior acoustic performance (Taban et al. 2020; Chanlert et al. 2023; Srisawas et al. 2024), highlighting the need for comprehensive material characterization in acoustic design.

Impregnation of wood with chemical and oil-based agents has been widely applied to improve physical performance, although the environmental impact of each treatment varies significantly. Zinc chloride ($ZnCl_2$), for example, reduces hygroscopicity and enhances thermal stability by promoting hemicellulose degradation and modifying pyrolysis behavior, as shown by a shift in the decomposition peak temperature and increased thermal residue (He et al. 2019). However, $ZnCl_2$ poses environmental risks due to its solubility and potential for leaching. Studies have indicated that chemicals like $ZnCl_2$ used in wood preservation can leach into the environment, negatively affecting soil health, ecology, and biodiversity (Meena 2022). Engine oil (EO), when used as a wood preservative, can significantly reduce water absorption and fungal colonization. According to Belchinskaya et al. (2021), EO-treated wood exhibited improved water resistance and reduced biodegradation, demonstrating enhanced durability. Similarly, Pereira et al. (2015) observed that wood impregnated with used EO showed greater resistance to xylophagous termites, suggesting potential for protective applications. Nevertheless, as a petroleum-based substance, EO may pose environmental risks if improperly disposed or leached into soil or water systems. Studies have shown that used engine oil contains heavy metals and polycyclic aromatic hydrocarbons (PAHs), which can contaminate soil and water, disrupt microbial communities, and pose health risks to humans and wildlife (Anoliefo and Vwioko 1995; Armioni et al. 2024). In contrast, coconut oil (CO), a biodegradable, bio-based oil, has emerged as a sustainable alternative. When used as a phase-change material, CO significantly increases the wood's thermal mass and energy storage capacity, nearly doubling its specific heat capacity, while maintaining environmental compatibility (Nazari et al. 2022).

Cajuput (*Melaleuca cajuputi* Powell) also known as Samet, Gelam, Galam, Paper bark tree, is a tree species widely distributed in Southeast Asia, particularly in Thailand, Myanmar, Cambodia, Vietnam and Malaysia. They are commonly found in coastal forests or cajuput-dominated woodlands (Department of National Parks, Wildlife and Plant Conservation, Thailand 2017). Cajuput is valued in forestry for its durability and versatility. The timber is moderately heavy, with an air-dry density ranging from 720 to 820 kg/m^3, and exhibits straight to shallowly interlocked grain, making it suitable for structural applications such as poles, fishing stakes, and piling works (Lim and Midon 2001). Mangium (*Acacia mangium* Willd.) is native to Papua New Guinea, Indonesia, and Queensland, Australia. It thrives in a variety of environments, including disturbed areas, open spaces, and grasslands (National Parks Board, Singapore 2022). Mangium is a fast-growing and highly adaptable species, widely valued in forestry for its versatility and applications. It is extensively cultivated for high-quality timber, used in pulp production, solid wood manufacturing, and energy generation, including charcoal and firewood (Koutika and Richardson 2019). Mango wood (*Mangifera indica*), a tropical wood species native to South Asia and widely cultivated in tropical and subtropical regions. Its fast growth makes it a sustainable option for forestry operations (Islam et al. 2022). It thrives in diverse habitats, including plantations and agroforestry systems, often in regions with warm climates and well-drained soils. Despite being classified as perishable due to its susceptibility to fungal decay, mango wood is highly valued for its versatility, particularly in interior applications such as furniture, paneling, and engineered wood products (Islam et al. 2022). The wood's density, ranging from 534 to 585 kg/m^3, along with its Modulus of Elasticity (MOE) and Modulus of Rupture (MOR), categorizes it as light construction timber suitable for furniture and interior frameworks (Zziwa et al. 2016).

Although Cajuput, Mangium, and Mango woods are abundant in tropical regions, studies on their acoustic performance remain limited—particularly regarding their potential as eco-friendly building materials. This study is among the first to systematically investigate the acoustic behavior of these tropical hardwoods following specific impregnation treatments. The focus is placed on evaluating their sound absorption characteristics across a wide frequency range. The paper presents a detailed analysis of how different treatments influence acoustic performance, supported by statistical evaluation using two-way ANOVA to assess the significance of the independent factors (wood type and treatment type) on key acoustic parameters. The findings are discussed in the context of sustainable building materials, highlighting the potential of treated tropical woods as viable, environmentally responsible acoustic materials.

2 Materials and methods

2.1 Preparation and impregnation of wood samples

To investigate the acoustic properties of Cajuput (*Melaleuca cajuputi* Powell subsp. *cumingiana* (Turcz.) Barlow), Mangium (*Acacia mangium* Willd.), and Mango (*Mangifera indica*) woods. The wood used was over 10 years old and sourced from Songkhla, Thailand. The samples were acclimatized by air-drying at ambient temperature (22–28 °C, 80–85% RH) for 3 days, followed by storage in a humidity-controlled cabinet at 25 °C and 45% RH for 2 days. They were prepared in cylindrical shapes with a uniform diameter of 28.6 mm and a thickness of 30 mm. This geometric configuration was chosen to ensure consistency in measurements of sound absorption using the impedance tube. The study included both untreated control samples and treated samples subjected to three types of liquid impregnations: The study included both untreated control samples and treated samples subjected to three types of liquid impregnations for 24 h under ambient conditions: 0.02% w/w zinc chloride ($ZnCl_2$) solution, prepared by dissolving $ZnCl_2$ powder (KemAus, New South Wales, Australia) in deionized water; two-stroke engine oil (EO) (Shell Advance, The Shell Company of Thailand Ltd., Thailand); and coconut oil (CO) (Yok brand, Lam Soon (Public) Co., Ltd., Thailand), both used in their original commercial forms. For each treatment group, three samples per wood type were prepared, resulting in a total of nine treated samples (3 treatments × 3 replicates). Additionally, three untreated samples were retained as control groups, making a total of 12 samples for each wood species. The material preparation procedure was illustrated in Fig. 1.

To assess the effects of the treatments, the density of each wood sample was measured before and after impregnation. This step quantified the degree of liquid retention, reflecting the wood's capacity to retain the respective treatment liquids ($ZnCl_2$, EO, and CO). Any surplus liquid on the surface of the samples was carefully removed prior to density measurement to ensure that only the liquid within the wood's internal structure was accounted for. After the liquid retention measurements, the samples were in ambient atmosphere for 5 days and then heated in an air-circulating oven at 105 °C for 3 h to remove the moisture and excessive treatment liquid. Once dried, the samples were stored in a humidity-controlled cabinet at 25 °C and 45% relative humidity for 2 days to stabilize their condition before acoustic analysis. The acoustic properties of the samples were then evaluated. Normal-incident sound absorption coefficients (SAC) were measured using an impedance tube, and the Sound Absorption Average (SAA) and Noise Reduction Coefficient (NRC) were calculated from the SAC spectrum

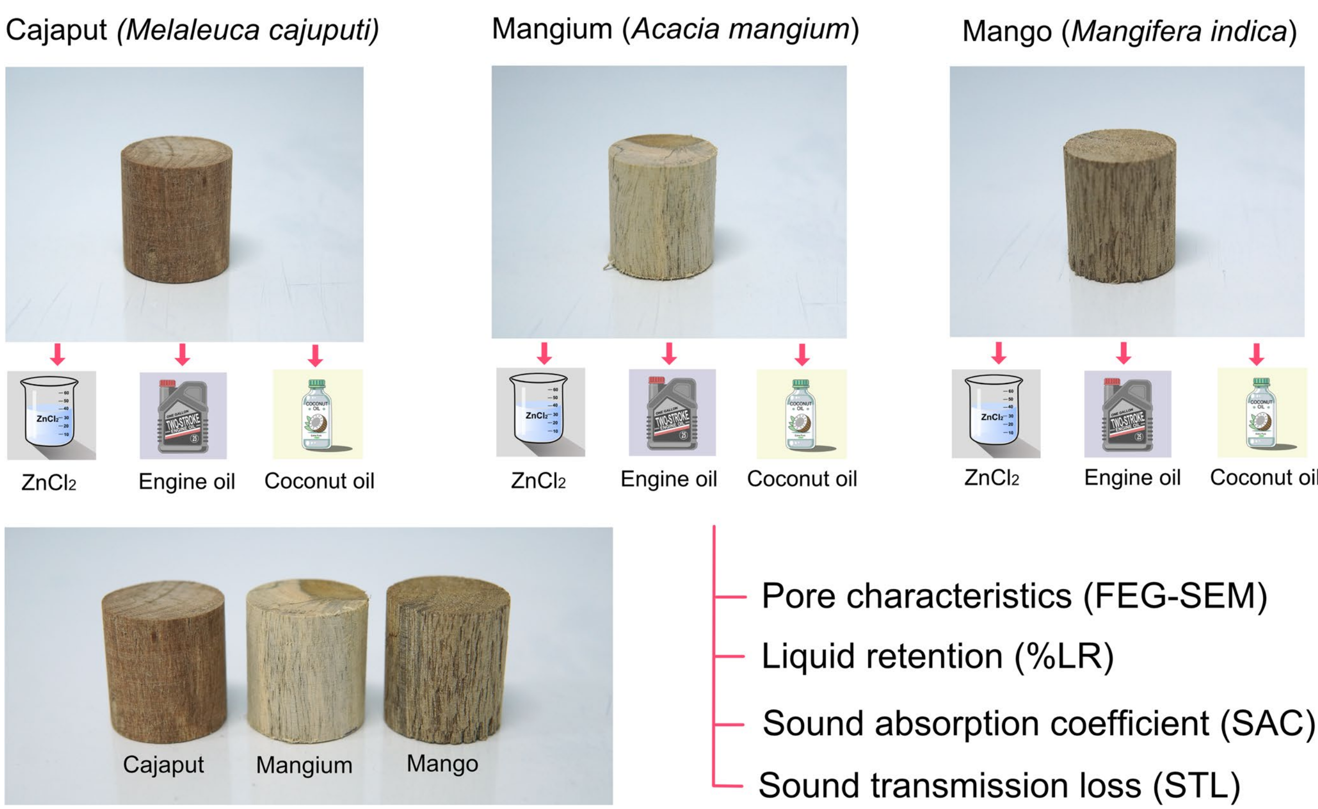

Fig. 1 Sample preparation process and the key measurements in this study

to quantify sound absorption efficiency. Additionally, Sound Transmission Loss (STL) spectra were obtained for each sample. From these spectra, the Transmission Loss Average (TLA) was derived as a single-number representation, providing a simplified metric for comparing the sound insulation performance of different treatments and wood types.

2.2 Acoustic property measurement

The normal-incident sound absorption coefficient (SAC) spectra of the wood samples were measured using a domestically built cylindrical two-microphone impedance tube (Chanlert et al. 2022b, 2024; Srisawas et al. 2024). This setup, shown in Fig. 2(a), adhered to ISO 10534-2 (ISO-10534 1998) and ASTM E1050-98 (ASTM-E1050 1990) standards, ensuring accurate and reliable measurements. The impedance tube utilized the transfer function method and was constructed from stainless steel, with an inner diameter of 28.6 mm, matching the dimensions of the wood samples. Two laboratory-grade microphones (GRAS 46BD-FV, GRAS Sound & Vibration, Denmark) were employed for precise sound measurement. A broadband noise source, generated by a full-range speaker, was directed at the sample mounted inside the impedance tube. The samples were securely held in place by a stainless steel rigid plate at the back to ensure consistent acoustic measurements. Data acquisition was performed using a data acquisition system (NI-9230 and cDAQ-9171, National Instruments, TX, USA). Python was used to collect, process, and analyze the sound data, enabling the calculation of the SAC spectrum for each sample.

The sound insulation properties of the wood sample were characterized using the sound transmission loss (STL) value, which indicates the reduction in sound level (in dB) after passing through the material. Measurements of normal-incident STL were conducted using a custom-built four-microphone impedance tube (Chanlert et al. 2022b, 2024; Srisawas et al. 2024), following the ASTM-E2611 standard (ASTM-E2611 2019), as illustrated in the schematic diagram in Fig. 2(b). A cylindrical wood sample with a diameter of 28.6 mm was positioned between microphones 2 and 3. Four laboratory-grade microphones (GRAS 46BD, GRAS Sound & Vibration, Denmark) were precisely placed to capture sound signals, which were then acquired using data acquisition devices (NI-9230 and cDAQ-9174, National Instruments, TX, USA). The transfer matrix method, as outlined in ASTM-E2611 standard, was employed to calculate the normal-incident STL values. The resulting STL spectra are presented in Figs. 7 and 8.

2.3 Statistical analysis

The ANOVA test provided valuable insights into the effects of wood type, treatment, and their interaction on both the non-acoustic and acoustic properties of the wood samples. Prior to performing the analysis in this study, the normality of the residuals was verified using the Shapiro-Wilk test, and all parameters satisfied the normality assumption. A two-way ANOVA was conducted using the statsmodels library in Python, incorporating both the treated and control groups in the analysis. The statistical model included two factors: wood type (3 levels: Cajuput, Mangium, Mango) and treatment type (3 levels: $ZnCl_2$, EO, CO), as described in the Materials and Methods section.

3 Results and discussions

3.1 General characteristics

The analysis of surface morphology was conducted to examine the microscopic structure of the wood samples, focusing on both longitudinal and cross-sectional views. A field-emission scanning electron microscope (FEG-SEM, Phenom Pharos G2, Thermo Fisher Scientific, UK) was used to capture high-resolution images of the wood samples.

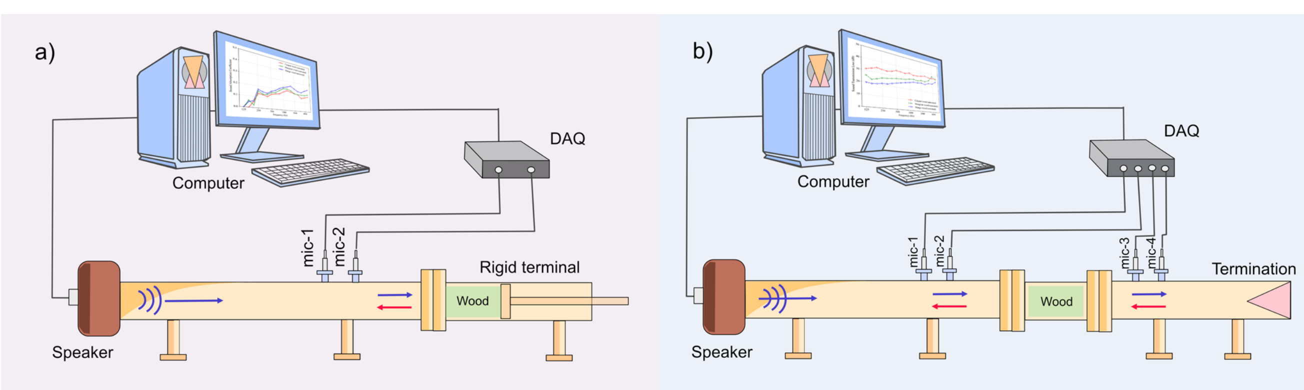

Fig. 2 Schematic diagram of **a** two-microphone impedance tube and **b** four-microphone impedance tube

The longitudinal morphology of intrinsic Cajuput, Mangium, and Mango woods is shown in Fig. 3(a), (b), and (c), respectively. The images reveal the presence of fibrous strips, which are components of the xylem or phloem tissues. Among the three wood species, the strips in Mangium are the smallest, resulting in the densest arrangement. This is followed by Cajuput and Mango wood, with Mango exhibiting the least dense structure. These morphological differences highlight the varying density and structural organization of the wood fibers, which influence their acoustic and mechanical properties.

For cross-sectional analysis, intrinsic wood samples were cut using liquid nitrogen to preserve structural integrity during preparation. The cross-sectional images are presented in Fig. 3(d), (e), and (f) for Cajuput, Mangium, and Mango wood, respectively. The images illustrate the xylem and phloem structures within the wood samples. The diameter of the xylem, the larger tubular structures responsible for water transport, ranges between 80 and 150 microns across all samples, with no significant variation in their characteristics. In contrast, the phloem, which facilitates nutrient transport, exhibits more pronounced differences among the wood species. The phloem in Cajuput and Mango wood tends to have a rectangular shape, while in Mangium, it displays a more curved structure. The size of the phloem tubes ranges between 20 and 30 microns. Additionally, the cross-sectional analysis reveals distinct surface characteristics. Mango wood shows a greater abundance of fluffy structures compared to Cajuput and Mangium. This is likely attributed to its classification as a softer wood, which results in a less compact structure and increased susceptibility to fluff formation during preparation.

3.2 Density and liquid retention

To evaluate the effects of liquid treatments on the wood samples, all specimens were soaked in zinc chloride ($ZnCl_2$), mechanical oil (MO), and coconut oil (CO) for 48 h. Density measurements were performed both prior to and after the treatments to determine the extent of liquid absorption and its influence on the wood's physical properties.

The untreated Cajuput wood exhibited the highest intrinsic density among the three wood species, followed by Mangium and Mango wood. Figure 4(a) illustrates the density of the samples before and after treatment. Specifically, the untreated Cajuput wood displayed an average density of approximately 800 kg/m^3, Mangium around 750 kg/m^3, and Mango wood the lowest at approximately 550 kg/m^3. These differences highlight the variation in intrinsic density and structural compactness across the three species.

To assess the statistical significance of density changes resulting from each treatment, paired t-tests (statsmodels library in Python) were conducted comparing the densities before and after impregnation for each wood type. The results revealed that $ZnCl_2$ significantly increased the density of all three wood species—Cajuput, Mangium, and Mango—with p-values below 0.05. For the EO treatment, significant density changes were observed only in Mango wood ($p = 0.0019$), whereas Cajuput and Mangium did not show statistically significant differences ($p = 0.0502$ and 0.0555, respectively). Similarly, CO treatment led to significant density increases in Cajuput and Mango ($p = 0.0373$ and 0.0041, respectively), while the change in Mangium was not statistically significant ($p = 0.0585$). These findings indicate that $ZnCl_2$ impregnation consistently alters wood density, while the effects of EO and CO treatments

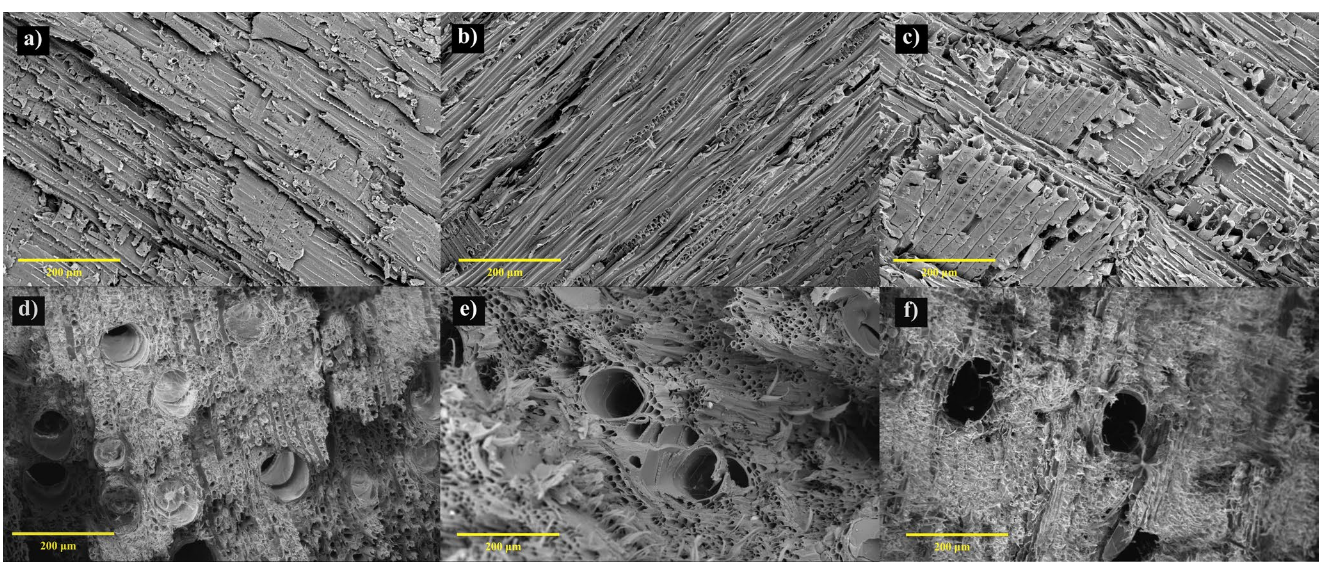

Fig. 3 FEG-SEM images of wood samples showing longitudinal surfaces of **a** Cajuput, **b** Mangium, **c** Mango; and cross-sectional surfaces of **d** Cajuput, **e** Mangium, **f** Mango

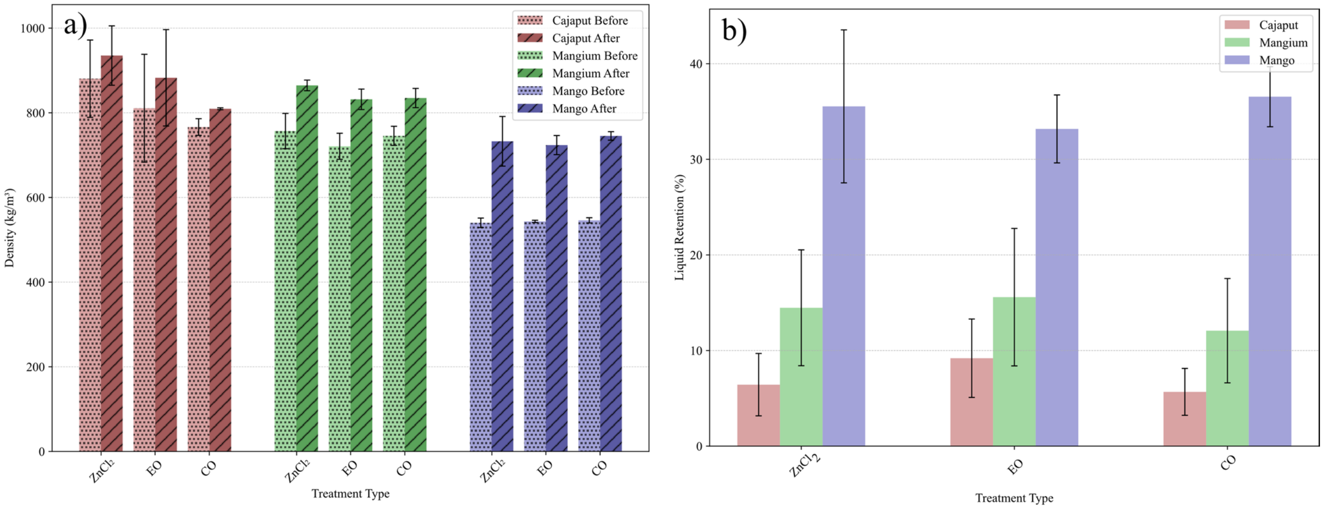

Fig. 4 **a** Sample densities before and after the treatments and **b** percentage of liquid retention

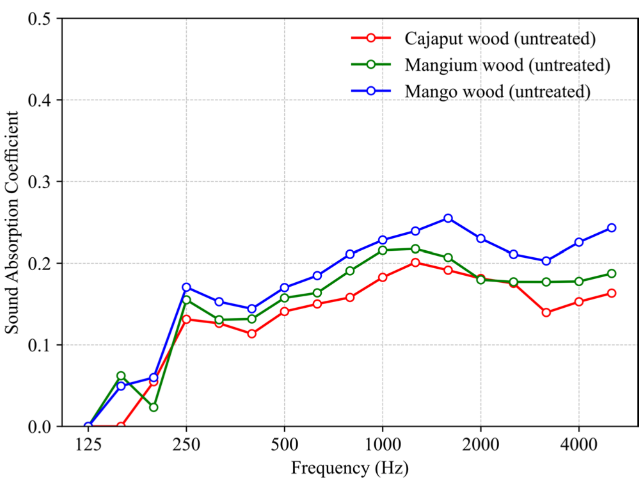

Fig. 5 Sound absorption coefficient spectra of untreated wood samples

are wood-dependent and more variable in their absorption behavior.

Figure 4(b) shows the liquid retention (%LR) of Cajuput, Mangium, and Mango woods after impregnation with $ZnCl_2$, engine oil (EO), and coconut oil (CO). Mango exhibited the highest retention across all treatments, with values of 35.9% for $ZnCl_2$, 33.9% for EO, and 36.7% for CO, indicating its high fluid uptake capacity. Mangium showed moderate retention values of 14.4%, 16.3%, and 12.6% for $ZnCl_2$, EO, and CO, respectively. In contrast, Cajuput had the lowest retention, with values of 6.5%, 9.2%, and 6.1%, suggesting limited permeability. These results demonstrate that wood structure significantly influences absorption behavior, with Mango being the most responsive to treatment. These findings suggest that the intrinsic density and porosity of the wood significantly influence their capacity to absorb liquid treatments, which may, in turn, impact their acoustic and other physical properties.

3.3 Sound absorption property

The normal-incident sound absorption coefficient (SAC) of the untreated samples was measured across the frequency range of 125–5000 Hz, as shown in Fig. 5. Among the untreated wood species, Mango wood exhibited the highest SAC throughout the measured frequency range, followed by Mangium and Cajuput. This result is consistent with the intrinsic properties of Mango wood, which demonstrated the highest liquid absorption and, consequently, higher open porosity. Open porosity, a key non-acoustical parameter, is positively correlated with SAC, as higher porosity generally enhances sound absorption. However, it is important to note that SAC is influenced by other parameters in addition to porosity.

For treated samples, SAC was measured after the samples had reached a stable weight, approximately three days after natural drying at ambient temperature. The SAC spectra of treated samples were generally higher than those of untreated samples. For Cajuput and Mango wood, coconut oil (CO) treatment showed the most significant improvement in SAC, particularly in the frequency range above 1000 Hz. In contrast, for Mangium, the SAC improvements were less distinguishable across the treatments, with no specific treatment consistently yielding the highest performance. A noticeable increase in SAC was observed around 2000 Hz, followed by a decrease around 3000–4000 Hz—a trend absent in the untreated samples. Based on our previous studies (Chanlert et al. 2024; Srisawas et al. 2024) and supported by the Johnson–Champoux–Allard (JCA) model (Allard et al. 1987; Johnson et al. 1987; Champoux and Stinson 1992), this behavior can be attributed to changes in pore structure caused by impregnation. Specifically, modifications in pore size, interconnectivity, and tortuosity likely

Table 1 Acoustic and non-acoustic properties of treated and untreated wood samples

Sample	SAA	NRC	α_L	α_M	α_H	TLA (dB)
Cajaput (control)	0.151	0.159	0.053	0.171	0.163	34.7
Cajaput ($ZnCl_2$)	0.180	0.192	0.083	0.202	0.216	21.1
Cajaput (EO)	0.228	0.242	0.099	0.251	0.306	20.0
Cajaput (CO)	0.231	0.255	0.095	0.241	0.313	21.4
Mangium (control)	0.163	0.177	0.082	0.192	0.180	28.4
Mangium ($ZnCl_2$)	0.203	0.212	0.093	0.222	0.254	21.8
Mangium (EO)	0.209	0.235	0.085	0.220	0.264	21.8
Mangium (CO)	0.211	0.227	0.084	0.223	0.292	22.4
Mango (control)	0.188	0.200	0.094	0.215	0.222	24.8
Mango ($ZnCl_2$)	0.211	0.221	0.099	0.240	0.243	19.4
Mango (EO)	0.194	0.203	0.093	0.220	0.230	19.9
Mango (CO)	0.224	0.236	0.103	0.244	0.301	18.3

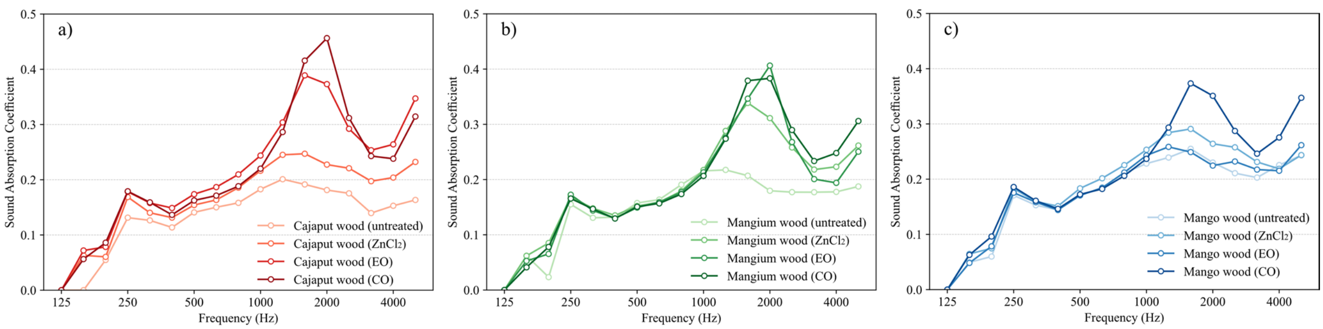

Fig. 6 Sound absorption coefficient spectra of treated wood samples of **a** Cajuput, **b** Mangium, and **c** Mango

enhanced energy dissipation at mid frequencies, while leaving the high-frequency-responsive pores relatively unaffected.

The Sound Absorption Average (SAA), a single-number metric representing the average sound absorption coefficient (SAC) across the 1/3 octave band frequencies between 200 and 4000 Hz, is summarized in Table 1. The Noise Reduction Coefficient (NRC), calculated as the average SAC at 250, 500, 1000, and 2000 Hz, was also determined. For most samples, SAA and NRC exhibit similar values, with treated samples showing consistent behavior in both metrics. However, NRC tends to be slightly higher than SAA in most cases. The CO treatment produced the highest SAA increase for all wood species. For Cajuput, CO treatment resulted in a 53% increase in SAA, the most substantial improvement among all samples. Similarly, CO treatment increased the SAA of Mangium and Mango wood by 29% and 19%, respectively. Engine oil (EO) treatment also improved SAA in most cases, though its effects were generally secondary to those of CO. Conversely, zinc chloride ($ZnCl_2$) treatment exhibited the weakest improvement in SAA across all wood types.

The sound absorption averages at low (α_L), medium (α_M), and high (α_H) frequency ranges (Chanlert et al. 2022a), are summarized in Table 1. The low frequencies are the 1/3 octave-band ranged from 125 to 400 Hz, the medium-frequency band covers 500 to 1600 Hz, and the high-frequency band includes 2000 to 5000 Hz. For Cajaput (Fig. 6(a) and Table 1), EO and CO treatments notably enhanced sound absorption at different frequencies, with EO achieving an outstanding 86.8% improvement of α_L and CO achieving a remarkable 92.0% improvement of α_H. EO also moderately improved α_M by 46.8%. $ZnCl_2$ treatment showed mild to moderate improvements across all frequency ranges but was less pronounced compared to EO and CO. For Mangium (Fig. 6(b) and Table 1), CO treatment provided the most notable enhancement, improving α_H by 62.2%. $ZnCl_2$ treatment mildly improved α_L by 13.4% and moderately enhanced α_M by 15.6%, but its overall effect was less impactful than CO. For Mango (Fig. 6(c) and Table 1), CO treatment showed the most significant impact, with 35.6% improvement of α_H. It also moderately improved α_M by 13.5% and mildly enhanced α_L by 9.6%, outperforming EO and $ZnCl_2$ treatments across all ranges.

3.4 Sound transmission loss

The sound transmission loss (STL) spectra, which evaluate the sound insulation properties of the wood samples, exhibited trends opposite to those observed in the sound absorption coefficient (SAC) measurements. As shown in Fig. 7, untreated mango wood displayed the lowest STL spectrum

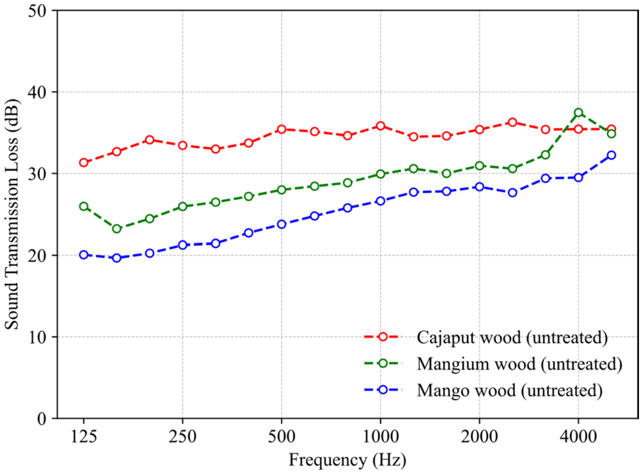

Fig. 7 Sound transmission loss spectra of untreated wood samples

among the untreated samples, while Cajuput exhibited the highest STL. This pattern aligns with the relationship between STL and porosity, as less porous materials generally demonstrate higher STL. These findings are consistent with prior studies on the acoustic properties of porous materials.

The Transmission Loss Average (TLA), a single-number metric representing the average STL across specified frequency bands (1/3 octave band frequency between 200 and 4000 Hz) (Srisawas et al. 2024), is summarized in Table 1. After treatment, a notable drop in TLA was observed across all wood species, as illustrated in Fig. 8. This reduction was most pronounced in Cajuput, which also exhibited the greatest SAC improvement. Specifically, the TLA of Cajuput decreased by 42% following engine oil (EO) treatment, representing the largest decline among the wood species. Mango wood showed the second-highest TLA reduction, with a 26% drop after coconut oil (CO) treatment. Mangium experienced a similar reduction, with TLA decreasing by 23% after treatment with both $ZnCl_2$ and EO.

According to Jang and Kang (2019), heat treatment notably affects the porosity and gas permeability of wood, primarily through the degradation of hemicellulose and the expansion of micro-pores in cell walls. As treatment temperature increases, through-pore porosity rises, enhancing gas permeability, while blind and closed pore porosities decrease. The increase in through-pore porosity improves sound absorption coefficients (SAC) but reduces sound transmission loss (STL) (Chanlert et al. 2022b, 2024; Srisawas et al. 2024), as greater porosity allows sound waves to penetrate more easily through the material's structure. This trade-off highlights a critical limitation of liquid impregnation combined with heat treatment: while SAC improves, STL is compromised. The choice of treatment should, therefore, depend on the intended application. For sound absorption, heat treatments are suitable, while untreated or alternative treatments are better for sound insulation. Striking this balance is crucial for optimizing the acoustic properties of wood.

3.5 Results for statistical analysis

According to Table 2, wood type showed a highly significant effect on liquid retention percentage (%LR) ($p < 0.001$) while it did not show a significant effect on SAA ($p = 0.673$) and NRC ($p = 0.959$). This indicates that the intrinsic differences among Cajuput, Mangium, and Mango woods did not substantially contribute to their sound absorption performance. In contrast, the effect of wood type on TLA was marginally significant ($p = 0.035$), suggesting that variations in sound insulation properties between the wood types were more distinct than those in their sound absorption characteristics.

Treatment effects were consistently significant ($p < 0.001$) for non-acoustic (%LR) and some acoustic metrics (SAA, NRC, α_L, α_M, α_H, and TLA), highlighting the considerable impact of treatments by soaking in liquid ($ZnCl_2$, EO, and CO) combined with heat treatment (105 °C for 3 h) on the acoustic performance of the woods. This result underscores the importance of chemical modifications combined with heat treatment in enhancing or altering the acoustic properties of wood materials. In contrast, the effect of treatment on α_M was marginally significant ($p = 0.018$), suggesting that variations in sound absorption at medium frequency range

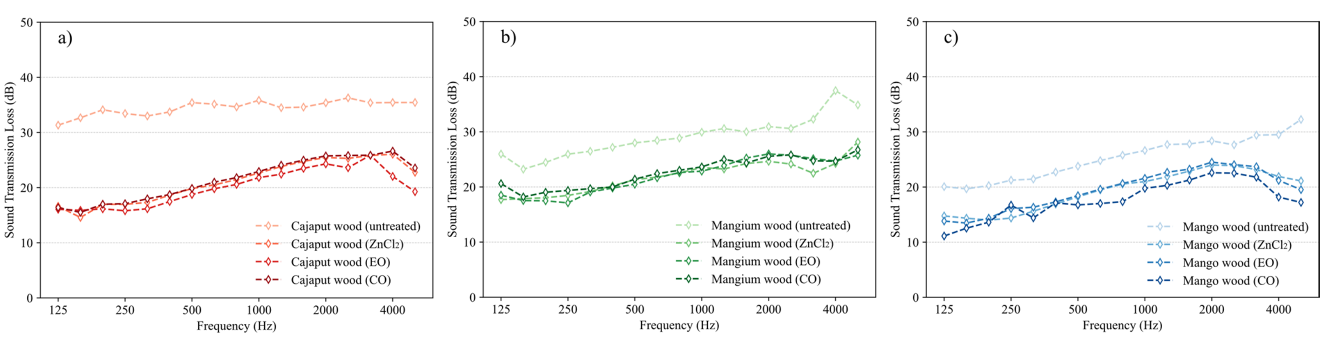

Fig. 8 Sound transmission loss spectra of treated wood samples of **a** Cajuput, **b** Mangium, and **c** Mango

Table 2 p-values from ANOVA of physical and acoustical properties of wood samples

Factor	%LR	SAA	NRC	α_L	α_M	α_H	TLA
Wood Type	< 0.001**	0.673	0.959	0.057	0.387	0.994	0.035*
Treatment	< 0.001**	< 0.001**	< 0.001**	0.055	0.018*	< 0.001**	< 0.001**
Wood Type · Treatment	< 0.001**	0.158	0.195	0.108	0.325	0.243	0.264
R-Square (adjusted)	89.6%	44.5%	38.7%	31.5%	23.3%	45.0%	56.1%
%CV	26.3%	9.7%	11.0%	13.5%	10.8%	14.9%	13.2%

* and ** indicate significance at the 95% and 99% confidence levels, respectively

Table 3 Comparative studies of sound absorption performance of wood species

Wood	Scientific name	Thickness (mm)	NRC	References
Cajuput	*Melaleuca cajuputi*	30	0.159	This study
Mangium	*Acacia mangium*	30	0.177	This study
Mango	*Mangifera indica*	30	0.200	This study
Malas wood	*Homalium foetidum*	10	0.10	(Kang et al. 2018)
Empress tree	*Paulownia totemtosa*	20	0.101	(Kang et al. 2019)
Balsa	*Ochroma lagopus Swartz*	10	0.109	(Jang and Kang 2021)
Binuang	*Octomeles sumatrana*	10	0.155	(Jang and Kang 2021)
Paulownia	*Paulownia coreana*	10	0.088	(Jang and Kang 2021)
Magas (Malaysian)	*Duabanga moluccana*	10	0.114	(Jang and Kang 2022a)
Yellow poplar (sapwood)	*Liriodendron tulipifera*	10	0.23	(Jang and Kang 2022e)

between each treatment were less distinct. Meanwhile, the effect of treatment on α_L is not significant as their confidence level is less than 95% (p= 0.055). Notably, the interaction between wood type and treatment was significant at 99% confidence level for liquid retention (%LR) with p< 0.001, suggesting that the effect of treatments on density gain varied depending on the type of wood. However, the interaction effects were not significant for all other parameters, suggesting that the improvements in noise reduction and sound insulation were relatively consistent across wood types regardless of the treatment applied.

The adjusted R-squared values revealed a strong explanatory power of the model for SAA ($R^2_{Adj.}$ = 0.896), while the models for NRC ($R^2_{Adj.}$ = 0.445) α_L ($R^2_{Adj.}$ = 0.315), α_M ($R^2_{Adj.}$ = 0.233), α_H ($R^2_{Adj.}$ = 0.450), and TLA ($R^2_{Adj.}$ = 0.561) explained moderate levels of variability. Additionally, the coefficients of variation (%CV) were low for SAA, NRC α_L, α_M, α_H, and TLA with %CV lower than 15%, suggesting consistent and reliable measurements for SAC and STL. In contrast, %LR showed a higher variability (%CV =26.3), reflecting greater experimental variation in liquid retention measurements.

3.6 Comparative studies

Table 3 displays the values of noise reduction coefficients (NRC) of the wood samples examined in this study—cajuput (*Melaleuca cajuputi*), mangium (*Acacia mangium*), and mango (*Mangifera indica*)—which were measured as 0.159, 0.177, and 0.200, respectively, for 30 mm thick specimens. Among these, mango wood demonstrated the highest NRC, indicating superior sound absorption performance in comparison to the other species in this study. This trend highlights the potential of mango wood for acoustic applications where noise attenuation is essential.

When compared to other wood species from related studies, the NRC of mango wood (0.200) significantly outperformed thinner specimens, such as malas wood (*Homalium foetidum*, 10 mm, 0.10) (Kang et al. 2018) and empress tree (*Paulownia tomentosa*, 20 mm, 0.101) (Kang et al. 2019). Similarly, mango wood exhibited higher NRC values compared to balsa (*Ochroma lagopus Swartz*, 10 mm, 0.109) and binuang (*Octomeles sumatrana*, 10 mm, 0.155) (Jang and Kang 2021), further emphasizing its sound absorption capabilities. Cajuput wood (0.159) and mangium wood (0.177) exhibit higher NRC values compared to paulownia (*Paulownia coreana*, 10 mm, 0.088) and magas (*Duabanga moluccana*, 10 mm, 0.114). However, this difference may be attributed to the greater thickness of the samples in this study, as sound absorption properties are influenced by material thickness. To ensure a rigorous comparison between these species, future studies should evaluate NRC values using samples of uniform thickness under similar testing conditions.

Interestingly, the sapwood of yellow poplar (*Liriodendron tulipifera*, 10 mm, 0.23) reported the highest NRC among the compared species, exceeding even mango wood despite its thinner specimen size. This suggests that yellow poplar sapwood may have unique structural or anatomical properties that enhance its acoustic performance, warranting further investigation.

To achieve more rigorous comparisons with previous studies, future research should focus on evaluating wood species at similar thicknesses, particularly in the 10–20 mm range, to standardize testing conditions and better understand the influence of thickness on NRC performance. Wood has served as a traditional construction material for centuries, but modern research presents opportunities to elevate its physical properties, such as sound absorption, flexural strength, and impact resistance, to higher performance levels. In addition to improving these physical properties, future research in wood science and technology could explore innovative treatments, hybrid wood composites, and the integration of bio-based materials to develop multifunctional wood products. Investigating the long-term durability and sustainability of treated wood in various environments is also crucial to advancing its role in construction and engineering applications.

4 Conclusion

This study evaluated the acoustic and non-acoustic properties of treated tropical woods—Cajuput, Mangium, and Mango—for potential applications in building materials.

- The liquid retention (%LR) highlighted the role of wood structure and treatment type in determining acoustic behavior. Mango wood exhibited the highest %LR (33.2–36.7%) due to its porosity, while Cajuput showed the lowest retention (< 10%).
- Coconut oil (CO) treatment was the most effective for enhancing sound absorption, increasing the Sound Absorption Average (SAA) by 53% in Cajuput and improving high-frequency absorption across all species.
- Engine oil (EO) preferentially enhanced sound absorption in the low to mid frequency ranges, while $ZnCl_2$ treatment had relatively lower effects on SAA across all species.
- Both EO and CO treatments led to a reduction in sound transmission loss (STL), with the most significant drop observed in Cajuput treated with EO (−42%), indicating a trade-off between absorption and insulation.
- Statistical analysis using two-way ANOVA confirmed significant effects of treatment type on all dependent variables (SAA, STL, %LR), while wood type showed a strong influence on %LR. A significant interaction effect was observed only for %LR, emphasizing the structural contribution to liquid uptake.

Future research should focus on hybrid treatment approaches, advanced pore structure analysis, leachability testing to assess environmental impact and additive fixation, and long-term performance evaluation to guide the development of sustainable, high-performance wood-based acoustic panels.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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