

UDC 620.22:678.746:534.83

DOI: 10.15587/1729-4061.2026.364889

The object of this study is sustainable acoustic panel materials for building noise-control and sound-insulation applications. The large-scale generation of expanded polystyrene (EPS) waste presents a significant environmental challenge due to its inherent resistance to natural degradation. Recycled expanded polystyrene (EPS) reinforced with coconut coir fibers was investigated as a potential material for these applications. The EPS waste was first dissolved in commercial gasoline (Pertalite) via cold dissolution, subsequently blended with 5–60 vol% coconut coir fibers, and fabricated into composites using standard casting techniques. The acoustic and mechanical properties of the resulting materials were evaluated using an impedance tube (ASTM E1050-98) and flexural testing (ASTM D790-03), respectively. Experimental results demonstrated that the optimal solvent-to-EPS ratio was 3:1, yielding a highly homogeneous matrix ideal for composite fabrication. Acoustic analysis revealed that most specimens achieved a sound absorption coefficient exceeding 0.2; the sole exception was the composite containing a 5 vol% fiber fraction, which recorded a value of 0.1 at 500 Hz. Furthermore, the sound absorption capacity consistently improved with increasing frequency, highlighting the efficacy of the composites across the mid- to high-frequency spectrum. Regarding mechanical performance, evaluations indicated that the composite incorporating a 30 vol% fiber fraction achieved the maximum flexural strength and modulus. Overall, these findings establish that bio composites derived from EPS waste and coconut coir fibers possess substantial potential as sustainable acoustic materials, delivering both functional performance and tangible environmental benefits

Keywords: *expanded polystyrene waste, coconut coir fibers, polymer composites, sound absorption, flexural properties*

IDENTIFYING THE STRUCTURE-PROPERTY RELATIONSHIPS IN RECYCLED EXPANDED POLYSTYRENE-COCONUT COIR FIBER BIOCOMPOSITES FOR ACOUSTIC APPLICATIONS

I Ketut Gede Sugita

Doctor of Materials*

ORCID: <https://orcid.org/0009-0004-7205-7572>

Ngakan Putu Gede Suardana

Corresponding Author

Professor of Materials Engineering

E-mail: npg@unud.ac.id

ORCID: <https://orcid.org/0000-0002-8146-571X>

Jefri S. Bale

Professor of Materials Engineering

Department of Mechanical Engineering

Universitas Nusa Cendana

Kupang, Nusa Tenggara Timur, Indonesia

ORCID: <https://orcid.org/0000-0001-9946-8110>

Cipk Kencanawati

Doctor of Materials

Department of Environmental Engineering**

ORCID: <https://orcid.org/0000-0003-1555-2804>

Putu Lokantara

Doctor of Materials (Composite)*

ORCID: <https://orcid.org/0000-0002-3184-5781>

*Department of Mechanical Engineering**

**Udayana University

Jimbaran, Badung, Bali, Indonesia, 80361

Received 06.04.2026

Received in revised form 29.05.2026

Accepted date 15.06.2026

Published date 30.06.20226

How to Cite: Sugita, I. K. G., Suardana, N. P. G., Bale, J. S., Kencanawati, C., Lokantara, I. P. (2026).

Identifying the structure-property relationships in recycled expanded polystyrene-coconut coir fiber biocomposites for acoustic applications. *Eastern-European Journal of Enterprise Technologies*, 3 (12 (141)), 6–17.

<https://doi.org/10.15587/1729-4061.2026.364889>

1. Introduction

The rapid development of modern industry has led to a significant increase in the production and use of synthetic polymer materials, particularly expanded polystyrene (EPS), commonly known as Styrofoam. While EPS is widely utilized

in the packaging, construction, and automotive sectors due to its lightweight structure, chemical stability, and excellent thermal insulation properties, its non-biodegradable nature has rendered it a major contributor to urban solid waste [1]. Because polystyrene requires hundreds of years to decompose naturally, it significantly exacerbates environmental degradation.

According to a World Environment Day 2025 report [2], global plastic production currently exceeds 400 million tons annually, with nearly half designated for single-use applications. Given its massive utilization – driven by ease of manufacture, low density, and cost-effectiveness [3] – and the fact that only a marginal proportion is successfully recycled, the remainder inevitably accumulates in landfills and aquatic ecosystems. This accumulation results in widespread ecological disruptions, including severe soil and water pollution. Consequently, mitigating this environmental burden requires a transition toward a circular economy. In this context, the primary challenge extends beyond merely reducing plastic consumption; it necessitates the development of innovative strategies to upcycle EPS waste into value-added materials. Such an approach not only aids in environmental protection but also offers economic benefits to local communities by monetizing otherwise discarded resources.

To achieve this upcycling, composite materials engineering offers a highly viable pathway, particularly through the incorporation of natural fibers. Coconut coir fiber, an abundant agricultural by-product in tropical countries such as Indonesia-recognized as the world's largest coconut producer-represents a promising reinforcement material. Although traditionally derived from coconut husk waste for products like mats, ropes, and fuel, and more recently utilized in geotextiles and furniture, the volume of unutilized coconut coir waste remains substantial. Crucially, the structural composition of coconut coir fibers features natural cavities (lacunae) along the fiber axis, which inherently enhances their acoustic and thermal insulation capabilities [4]. Previous study conducted by [5] on hybrid composites comprising gypsum, pumice, adhesive, and coconut coir fiber demonstrated excellent sound absorption performance, achieving a coefficient of 0.927.

Building upon these findings and addressing the dual challenges of synthetic and agricultural waste management, this study aims to develop a sustainable sound-absorbing composite utilizing EPS waste as the polymer matrix and coconut coir fiber as the reinforcement. A critical methodological challenge in repurposing EPS, however, lies in its effective dissolution. While previous studies have employed thermal melting or various chemical solvents – such as acetone [6] or gasoline – many conventional solvents, including benzene, toluene, xylene, chloroform, and tetrahydrofuran, pose significant environmental and health risks, making them incompatible with green chemistry principles [7]. To circumvent the toxicity associated with solvents like acetone and methylene chloride, this study utilizes commercial-grade gasoline (Pertalite) as the EPS solvent. This approach is not only more cost-effective but also facilitates EPS liquefaction at room temperature, thereby eliminating the emission of hazardous combustion fumes associated with thermal processing.

Porous materials based on natural fibers are now receiving significant attention in the development of sustainable acoustic materials. Previous studies have confirmed that the sound absorption performance of these materials is highly dependent on airflow resistance, porosity, and tortuosity, which collectively govern the process of converting acoustic energy into heat [8, 9]. Specifically, natural fibers such as coconut husk exhibit superior acoustic characteristics due to their hollow structure and surface roughness, which effectively enhance sound wave scattering mechanisms and energy dissipation [10]. In line with this, recent innovations in biocomposites demonstrate that integrating porous structures with polymer matrices can significantly enhance sound absorption capacity while maintaining mechanical integrity [11, 12].

Therefore, amidst the escalating environmental crisis caused by the accumulation of expanded polystyrene (EPS) waste, as well as the surging demand for eco-friendly acoustic materials, the development of composite sound absorbers utilizing this waste is a highly relevant and urgent step.

2. Literature review and problem statement

The transformation of Styrofoam waste into a polymer matrix for composite materials represents a highly sustainable approach to mitigating plastic pollution. Several studies have demonstrated that thermoplastic wastes, such as high-density polyethylene (HDPE), high-impact polystyrene (HIPS), and general-purpose polystyrene, can be engineered into structural or functional composites exhibiting competitive mechanical, thermal, and acoustic properties. For instance, in work [3] formulated a roofing tile composite utilizing an amalgamation of sand and reclaimed HDPE, which demonstrated augmented hydrothermal resistance and flexural robustness commensurate with elevated HDPE loading. Corroborating these observations, in paper [13] delineated that HIPS composites fortified with rice straw fibers attained an elastic modulus surpassing 4900 MPa. Cumulatively, these empirical findings substantiate the efficacy of reclaimed thermoplastics as robust structural matrices.

Although these studies confirm the mechanical viability of recycled polymer composites, study has primarily focused on their structural applications, whereas the acoustic properties of these materials have largely been overlooked. Recycled polymers are typically evaluated for their strength, thermal insulation, or dimensional stability. However, the correlation between the porous microstructure of these materials and their sound-damping mechanisms has not been adequately explored. Consequently, the potential of utilizing recycled Styrofoam waste as a functional acoustic material warrants further investigation.

Within the paradigm of sustainable acoustic materials, natural lignocellulosic fibers have increasingly attracted substantial scholarly scrutiny. This trajectory is propelled by their intrinsic physicochemical attributes, encompassing low specific gravity, superior recyclability, and a highly porous morphology. Extant literature has established that natural fibers – namely coconut coir, kenaf, rice straw, and oil palm empty fruit bunches – manifest exceptional sound absorption coefficients. This acoustic proficiency is ascribed to the prevalence of internal micro-voids, pronounced surface topographical roughness, and an interconnected reticular pore network. Such structural configurations precipitate the dissipation of acoustic wave energy via interfacial friction and vibro-thermal conversion mechanisms intrinsic to the material matrix [8, 9].

Furthermore, contemporary investigations have underscored the viability of polystyrene-based composites fortified with bio-fillers and natural constituents for sustainable engineering deployments. In paper [14], reported that the addition of a biofiller derived from snail shell powder to a polystyrene matrix improved the mechanical performance of the composite due to better filler dispersion and stronger interactions between the matrix and the filler. Their findings highlight the importance of microstructural homogeneity and interfacial adhesion in determining the overall behavior of polystyrene-based composites.

In addition to their mechanical properties, natural fiber composites have shown considerable potential for acoustic damping applications. In paper [15] elucidated that porous natural substrates and sandwich-structured composites display superlative sound absorption characteristics, a phenomenon predicated upon interconnected pore networks that facilitate acoustic energy dissipation. Analogously, in work [16] articulated that green composites reinforced with natural fibers can attain a sound absorption coefficient surpassing 0.8 at elevated frequencies. Congruent with these observations, in work [17] discerned that coconut fiber-based porous composites manifest profound acoustic attenuation within the 2000–4000 Hz frequency spectrum, propelled by augmented airflow resistivity and internal frictional dynamics.

Synthesizing these perspectives, extant study postulates that the sound absorption mechanism within composite materials is fundamentally governed by pore morphology, fiber architecture, and internal spatial connectivity. Acoustic attenuation in natural fiber composites is predominantly ascribed to viscous friction, thermal dissipation, and complex internal reflections propagating through interconnected pore channels [15–17]. Concurrently, microstructural parameters, particularly filler distribution homogeneity and matrix–filler interfacial adhesion, strongly influence the mechanical properties of polystyrene-based composites [14].

Despite previous studies have extensively explored polystyrene-based composites and natural-fiber acoustic materials, limited study has investigated the combined influence of fiber volume fraction on the pore morphology, acoustic attenuation, and flexural behavior of recycled EPS-based composites. Consequently, the complex interplay among fiber content, pore development, interfacial bonding, and overall composite performance remains insufficiently understood. Investigations pertaining to polystyrene-based composites have predominantly fixated on thermal and mechanical properties, largely to the exclusion of their acoustic performance [14]. Conversely, the majority of inquiries into natural fiber-reinforced acoustic materials have concentrated exclusively on sound absorption metrics, offering a markedly deficient analysis of the concomitant mechanical responses [15–17]. Furthermore, the intricate correlations interlinking fiber volume fraction, micro-pore evolution as characterized via scanning electron microscopy (SEM), acoustic attenuation behavior, and flexural robustness have yet to be systematically appraised, particularly concerning composites that utilize reclaimed expanded polystyrene (EPS) waste as the continuous matrix.

While there have been previous studies on polystyrene-based composites and natural fiber acoustic materials, study investigating the combined acoustic and mechanical performance of recycled EPS composites reinforced with natural fibers remains limited. In particular, the relationship between fiber volume fraction, pore morphology, interfacial bonding, acoustic absorption, and flexural behavior is not yet fully understood.

3. The aim and objectives of the study

The aim of this study is to determine the structure-property relationships among fiber volume fraction, pore morphology, acoustic attenuation, and flexural behavior in recycled EPS-coconut fiber bio composites. This will provide a scientific basis for optimizing sustainable

acoustic panel materials derived from recycled polymers and agricultural waste for noise control and sound insulation applications in buildings.

To achieve this aim, the following objectives have been accomplished:

- to determine the optimal solvent composition for dissolving Styrofoam;
- to analyze the effect of fiber volume fraction on sound absorption performance;
- to evaluate the mechanical properties of the composites;
- to investigate the relationship between microstructure and acoustic behavior.

4. Materials and methods

The object of this study is sustainable acoustic panels and sound insulation materials for building applications. Recycled EPS-coconut coir fiber composites were investigated as candidate materials for these applications.

The study is predicated on the hypothesis that an increase in the fiber volume fraction will enhance sound absorption performance by augmenting the porosity within the composite structure. Conversely, it is anticipated that excessive fiber content will compromise mechanical strength due to weak interfacial bonding between the polymer matrix and the reinforcing fibers. To isolate these variables, the study assumes homogeneous material mixing and consistent specimen geometry throughout the fabrication process. Furthermore, the experimental design adopts specific simplifications, notably neglecting the potential influence of environmental factors, such as humidity and temperature fluctuations, during specimen preparation and testing.

The fabrication of these composites utilized Styrofoam waste sourced from Denpasar City, with Peralite gasoline serving as the solvent for polymer dissolution. Additional materials included sodium hydroxide (NaOH) for the chemical treatment of the fibers, glycerin, distilled water, and coconut coir fibers, which acted as the primary reinforcement. The experimental apparatus comprised digital scales, a specimen press machine, an impedance tube, and a universal testing machine. For specimen casting, cylindrical molds (100 mm in diameter and 10 mm in thickness) and square molds (200 × 200 × 10 mm) were employed.

The preparation of the coconut coir fibers commenced with mechanical cleaning to eliminate dust and surface impurities. This was followed by an alkali treatment utilizing a 6% NaOH solution (6 g NaOH per 94 mL of distilled water). To effectively remove wax, hemicellulose, and other non-cellulosic components – thereby enhancing the fiber–matrix interfacial adhesion – the treatment was conducted at a fiber-to-solution ratio of 1 g to 40 mL, maintained at 95°C for 3 hours [18]. Following the chemical treatment, the fibers were thoroughly rinsed with running water until no residual NaOH remained. Subsequently, the fibers were oven-dried at 70°C for 24 hours [19] to guarantee the complete eradication of moisture prior to further processing.

Concurrently, the polymer matrix was prepared by shredding the Styrofoam waste into small particulates to facilitate rapid dissolution. These particulates were then dissolved in gasoline at a volumetric ratio of 1:3 (gasoline to Styrofoam) until a highly homogeneous matrix was achieved. Once the matrix was stabilized, the treated coconut coir fibers were systematically incorporated into the Styrofoam solution at varying volume fractions of 5%, 10%, 15%, 20%, 30%, 40%, 50%, and 60%.

Upon achieving a uniform dispersion of fibers within the matrix, the mixtures were cast into the designated molds: cylindrical specimens for acoustic evaluation and square specimens for mechanical characterization. To ensure optimal compaction and mitigate internal voids, a constant compressive load of 40 kg was applied to the molds for 24 hours. Following the curing and drying phases, the consolidated specimens were demolded and conditioned at ambient room temperature prior to testing.

To evaluate the acoustic performance, the sound absorption coefficient of the cylindrical specimens was measured using an impedance tube apparatus, strictly adhering to the ASTM E1050-1998 standard [19, 20]. The schematic of this experimental setup is illustrated in Fig. 1 (ASTM E1050-1998 Impedance Tube Schematic).

During the experimental procedure, sound waves generated by a signal generator are emitted through a loudspeaker and directed into the impedance tube. As these waves impinge upon the specimen, a portion of the acoustic energy is absorbed by the composite structure, while the residual energy is reflected. The incident and reflected waves are subsequently measured by precisely calibrated microphones and analyzed using the transfer function method across a frequency range of 300–4000 Hz [15, 19, 21].

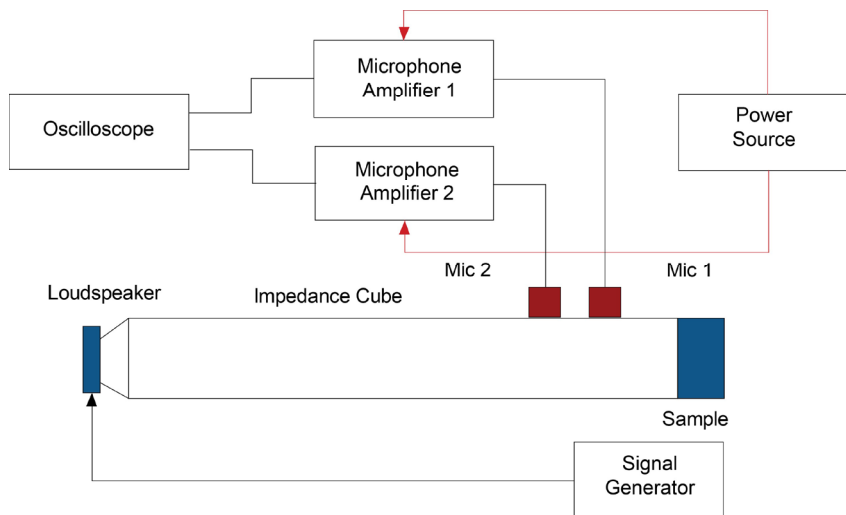


Fig. 1. ASTM E 1050-1998 impedance tube schematic

Flexural properties were evaluated using a three-point bending test in accordance with the ASTM D790-03 standard [21], with the experimental configuration illustrated in Fig. 2. During this procedure, each specimen was supported across a specified span and subjected to a central load until failure. As a result, the applied loading induced compressive stress on the upper surface and tensile stress on the lower surface of the specimen. Subsequently, the flexural stress, strain, and modulus were calculated using the standard equations outlined in the ASTM protocol.

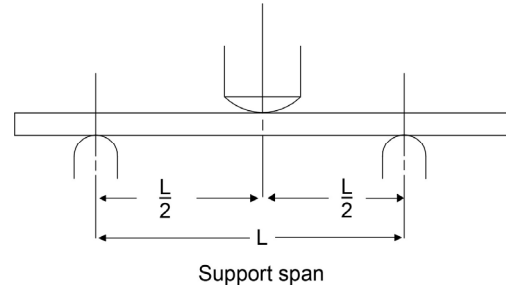


Fig. 2. Three-point bending

The flexural stress, flexural modulus of elasticity, and flexural strain were calculated according to the following equations:

Bending stress

$$\sigma = \frac{3PL}{2bd^2} \tag{1}$$

Bending strain

$$\epsilon = \frac{6\delta \cdot d}{L^2} \tag{2}$$

Bending modulus

$$E = \frac{L^3 \cdot m}{4b \cdot d^3} \tag{3}$$

where σ – flexural stress at the center of the support span (MPa); P – applied load (N); L – support span length (mm); b – specimen width (mm); d – specimen thickness (mm); E – flexural modulus (MPa); m – slope of the initial linear portion of the load-deflection curve (N/mm); ϵ – flexural strain (mm/mm); D – maximum specimen deflection (mm).

5. Results of sound absorption, mechanical, microstructural and chemical characterization

5.1. Determination of optimum Styrofoam solvent composition

Data on the dissolution of Styrofoam with various solutions is shown in the Table 1 below.

Table 1

Dissolution of Styrofoam

No.	Solution and composition (ml)	Styrofoam (gr)	Result
1	Toluene (100 ml)	33 gr	Styrofoam did not melt
2	Acetone (100 ml)	33 gr	Styrofoam melted but not sticky or binding
3	Pertalite gasoline (100 ml)	100 gr	Pertalite gasoline was insufficient for melting Styrofoam
4	Pertalite gasoline (100 ml)	50 gr	Pertalite gasoline was insufficient to melt Styrofoam
5	Pertalite gasoline (100 ml)	33 gr	Pertalite gasoline was capable of completely dissolving Styrofoam and had the fastest solidification process
6	Pertalite gasoline (100 ml)	20 gr	Pertalite gasoline was able to dissolve Styrofoam, but the solidification process took longer
7	Pertalite gasoline (100 ml)	10 gr	Pertalite gasoline was able to dissolve Styrofoam, but the result was too liquid, making it difficult to mold and take too long to compact

Preliminary tests evaluating three solvent types demonstrated that Pertalite gasoline was the most suitable, as it efficiently dissolved the Styrofoam and facilitated robust bonding with the coconut coir fibers. Building upon this, subsequent investigations into the solvent-to-Styrofoam proportions revealed an optimal mixture of 100 mL of Pertalite to 33 g of Styrofoam, corresponding to a 3:1 ratio. Consequently, this standardized ratio was adopted for the preparation of all specimens in the ensuing experiments.

5. 2. Effect of fiber fraction on sound absorption

Fig. 3 presents the sound absorption coefficients of Styrofoam-coconut fiber composites across various fiber fractions

and frequencies (300–4000 Hz). To facilitate comparison, the data are grouped into low-fiber-fraction (5–20%, Fig. 3, a) and high-fiber-fraction (30–60%, Fig. 3, b) categories.

In general, the sound absorption coefficient increases with increasing frequency, although fluctuations are observed across all compositions. At low frequencies (300–1000 Hz), most specimens exhibit minimal absorption, rendering them less effective at damping long-wavelength sound. For example, the 5% fiber-fraction composite yields the lowest absorption coefficient (0.11 at 600 Hz). This indicates an insufficient porous structure to effectively dissipate sound energy.

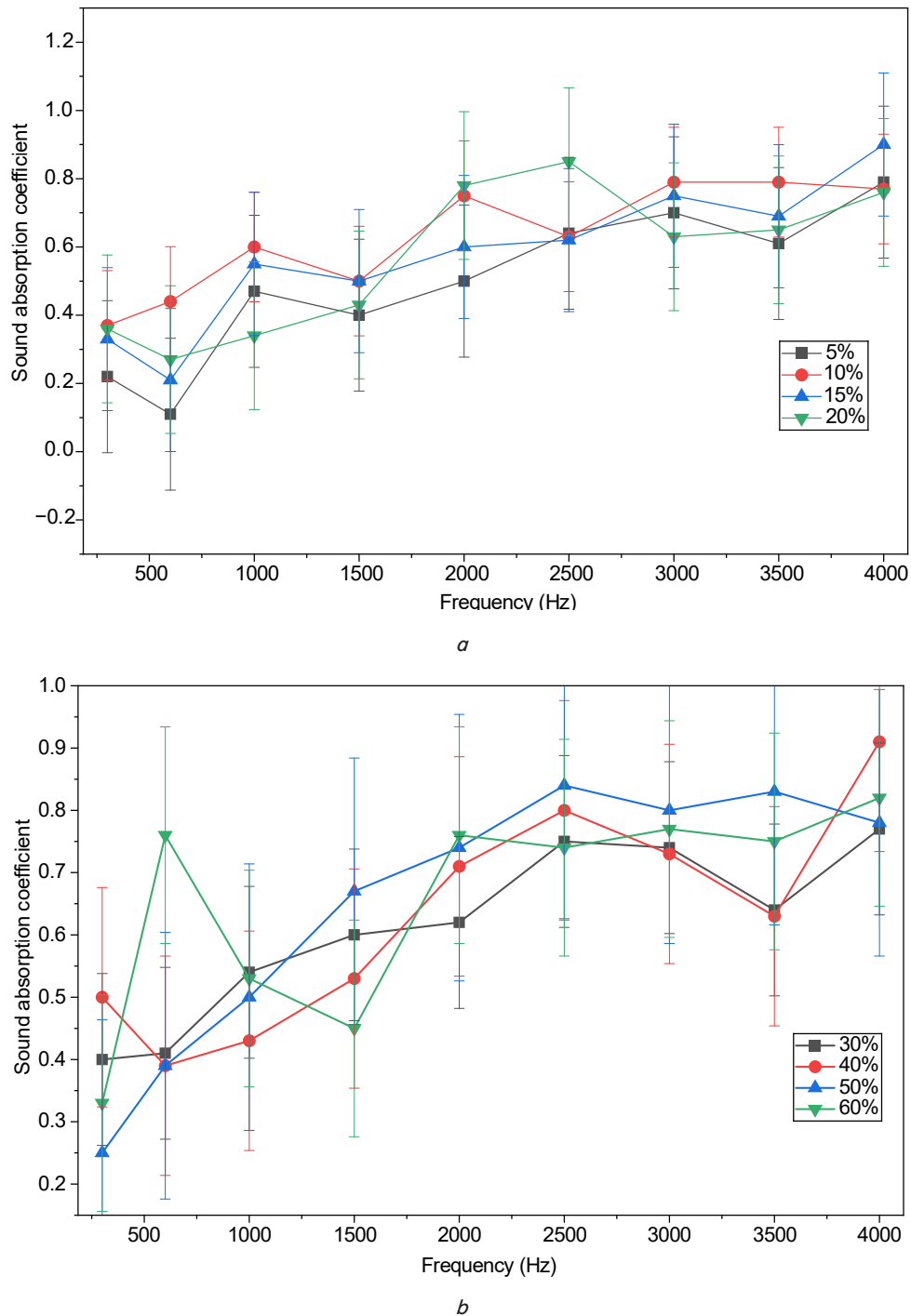


Fig. 3. Relationship between sound frequency and sound absorption coefficient of the composite material: a – low-fiber-fraction (5–20%); b – fiber-fraction (30–60%)

At mid-frequencies (1500–2500 Hz), the absorption coefficients of all compositions increase significantly. Composites with 20–50% fiber content exhibit higher and more stable absorption than the low-fiber groups. A more uniform fiber distribution within the Styrofoam matrix drives this improvement by forming interconnected pores that trap sound energy. Additionally, the hollow internal structure of the coconut fibers increases air friction and viscous losses. This mechanism effectively converts acoustic energy into heat, thereby optimizing sound absorption [15].

At high frequencies (3000–4000 Hz), all specimens exhibit excellent sound absorption (coefficients > 0.60). Peak performance (0.91 at 4000 Hz) is achieved by the composite with a 40% fiber fraction. This fraction provides an optimal balance between porosity and structural integrity, allowing sound waves to penetrate and maximize energy dissipation. Theoretically, pores and voids are crucial for sound absorption because the interaction between air particles and pore walls generates frictional losses [22]. Increasing the pore volume enhances the material's capacity to absorb sound energy [23] by converting acoustic energy into heat and mechanical vibrations until it is fully dissipated.

However, increasing the fiber fraction beyond the optimum point (50–60%) triggers fluctuations and a slight decrease in the absorption coefficient at certain frequencies. Fiber agglomeration and reduced inter-pore connectivity likely cause this decrease by restricting airflow into the material and increasing sound reflection. These findings align with the literature [24], which reports that low-density coconut fiber particleboards absorb sound more effectively due to their high porosity.

In conclusion, a non-linear relationship exists between the fiber fraction and sound absorption performance. A fiber fraction that is too low limits porosity formation, whereas an excessive addition reduces the material's structural homogeneity. A fiber fraction range of 30–40% represents the optimal balance between mechanical integrity and acoustic performance.

5.3. Mechanical characterization of composites

The mechanical characterization was conducted to evaluate the flexural behavior of Styrofoam-coconut fiber composites under flexural loading. The analysis included tests for flexural stress, flexural strain, and flexural modulus in accordance with ASTM D790-03 to determine the effect of fiber volume fraction on the mechanical performance of the composites.

Bending stress testing. The results of the bending stress testing of Styrofoam-coconut coir composites with varying fiber volume fractions are shown in Fig. 4. The bending stress values obtained changed significantly as the percentage of fiber in the composite increased. At fiber fractions of 10% and 15%, the bending stress was still relatively low at 0.13 MPa and 0.27 MPa, respectively.

These values indicate that at low fiber fractions, the role of coconut coir in withstanding bending loads is not yet optimal due to the limited bond between the Styrofoam matrix and the fibers. An increase in bending stress began to be seen at a fiber fraction of 20% and continued to rise until it reached a maximum value at a fraction of 30%. The bending stress of

0.35 MPa at 20% increased to 0.92 MPa at a 30% fiber fraction. This increase indicates that at this composition, the distribution of fibers within the matrix is sufficiently homogeneous, and the fibers are well bonded, thereby improving the composite's ability to withstand bending loads. After reaching a maximum point at 30%, the bending stress value decreased to 0.55 MPa at a fiber fraction of 40% and 0.36 MPa at a fiber volume fraction of 50%. This decrease is thought to be caused by fiber agglomeration, which results in uneven bonding between the fibers and the matrix. However, at a fiber fraction of 60%, the stress value increased slightly to 0.44 MPa, indicating that despite fiber agglomeration, some force could still be transmitted through sufficient fiber-to-fiber contact. Overall, the test results show that increasing the fiber volume fraction up to 30% has the most significant effect on enhancing the composite's bending strength. Beyond this composition, the addition of fibers no longer provides a significant increase in strength and tends to decrease it. This is because the addition of fibers causes less matrix to be used, which reduces the matrix's ability to bind the fibers, resulting in the addition of pores in the specimen [25]. Therefore, a fiber fraction of 30% can be categorized as the optimum composition for producing the highest bending strength in Styrofoam-coconut coir composites. These results are also in line with the study by [26] namely the study on flax fiber/Styrofoam waste composites, which obtained the highest bending stress at a composition of 30wt% flax fiber.

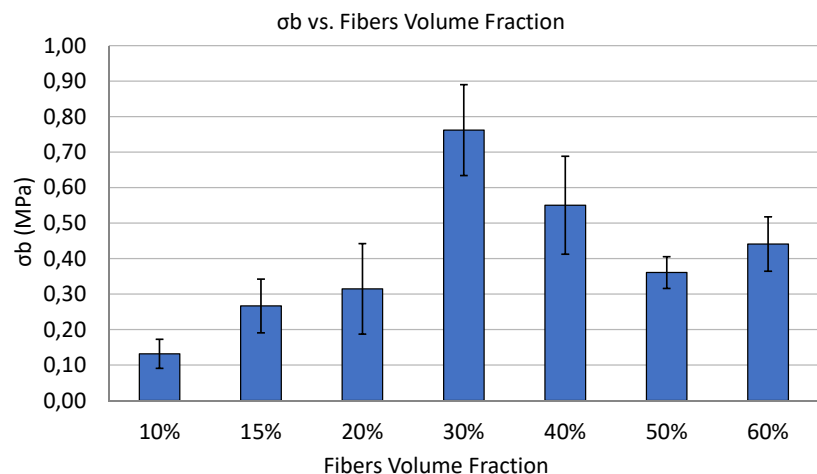


Fig. 4. Graph of the relationship between fiber volume fraction and bending stress

Bending strain testing. The relationship between composite fiber volume fraction and bending strain is presented in Fig. 5.

The results indicate that increasing the fiber volume fraction generally contributes to an increase in bending strain, although the trend exhibits fluctuations, reflecting the complex influence of microstructural factors, such as fiber dispersion and interfacial adhesion between the fibers and the matrix. At a 10% fiber volume fraction, the recorded strain was 0.23, indicating the initial contribution of fibers to the composite's flexural deformation capacity. This value slightly decreased to 0.22 at 15%, suggesting the formation of an initial reinforcement system in which the mechanical interaction between the matrix and the fibers began to effectively resist flexural loads. When the fiber fraction increased to 20%, the strain rose to 0.24, indicating a more effective load-sharing mechanism between the matrix and the reinforcing fibers. Interestingly, at a 30% fraction, the strain decreased to 0.20, which may be attributed to a more uniform stress transfer

throughout the fibers, thereby reducing the resulting deflection. This reduction suggests that the fibers begin to play a more dominant role in resisting bending strain, while the matrix continues to function as a binding medium. A notable increase in strain was observed at a 40% fiber fraction, reaching 0.35, indicating that the fiber-matrix ratio had exceeded the optimal equilibrium composition. This phenomenon commonly occurs when the fiber content surpasses the matrix's ability to adequately wet the fibers, resulting in some fibers becoming less effective in resisting flexural deformation and leading to greater deflection. At a 50% fiber fraction, the strain decreased again to 0.29, before increasing slightly to 0.32 at 60% fiber content. Despite these fluctuations, the strain values at higher fiber fractions remained greater than those observed at 10%, 15%, 20%, and 30%, indicating that at elevated fiber contents, interfacial cohesion decreases and the formation of microvoids increases due to non-uniform matrix dispersion. This condition may lead to the development of localized weak points within the composite structure, thereby reducing mechanical strength and resulting in greater deflection.

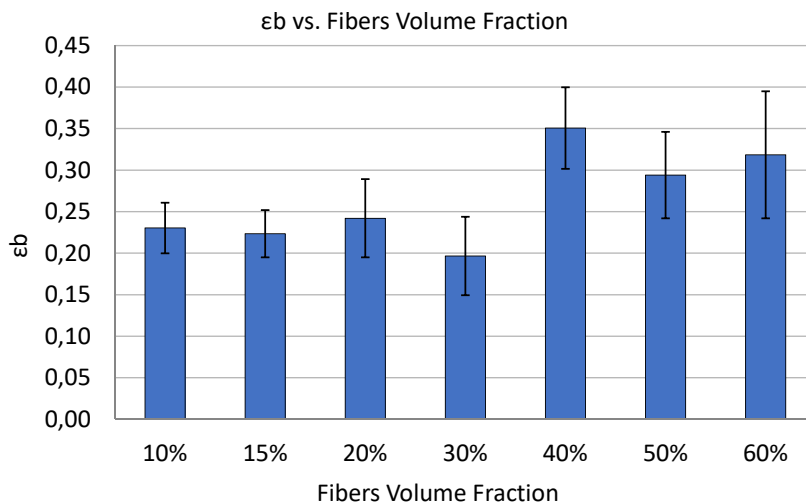


Fig. 5. Graph of the relationship between fiber volume fraction and bending strain

Overall, the relationship between fiber volume fraction and bending strain exhibits a non-linear trend, characterized by an initial increase in strain up to a certain fiber fraction, followed by a decrease and a subsequent increase at higher fiber contents.

Bending modulus. Based on the obtained data, an increase in the fiber volume fraction up to 30% resulted in a significant improvement in the elastic modulus, reaching a maximum value of 36.57 GPa. This increase reflects the effective interaction between the coconut coir fibers and the dissolved polystyrene (Styrofoam) matrix, where the fiber distribution within this range remains relatively homogeneous and capable of effectively resisting bending deformation. However, beyond this optimum composition, a drastic reduction in the elastic modulus was observed. At fiber fractions of 40–60%, the modulus decreased sharply to below 1 GPa. This phe-

nomon indicates that excessive fiber content reduces the integrity of the interfacial bonding, as the matrix is unable to sufficiently bind all fibers, leading to the formation of voids within the matrix (Fig. 6).

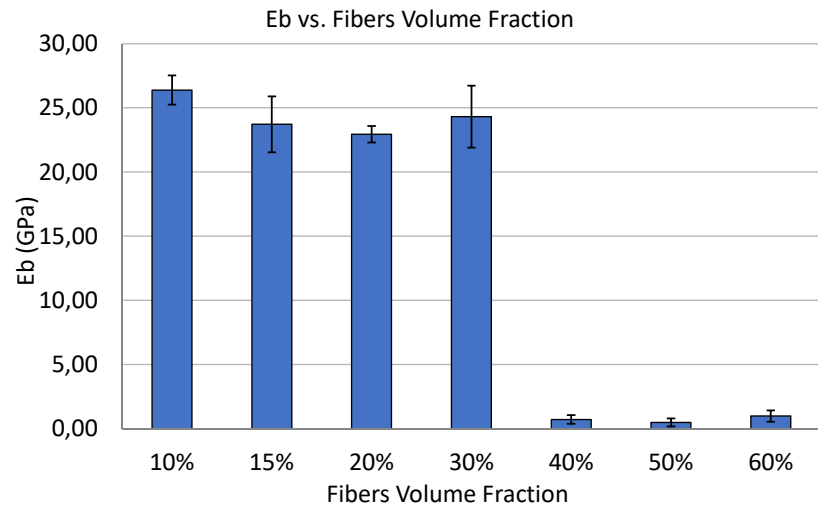


Fig. 6. Graph of the relationship between fiber volume fraction and bending modulus

Consequently, inefficient stress transfer between the matrix and the fibers significantly reduces the stiffness of the composite. The decrease in flexural stiffness at higher fiber fractions indicates that excess fibers lacking adequate matrix support render the composite brittle and diminish its elasticity. Furthermore, insufficient matrix content restricts interfacial bonding, potentially inducing localized delamination under applied loads. Overall, these findings establish a fiber fraction of 30% as the optimal composition to maximize stiffness in Styrofoam-coconut fiber composites, effectively balancing stress transfer and elasticity. Exceeding this threshold degrades the mechanical properties due to poor interfacial adhesion and microstructural inhomogeneity.

5. 4. Microstructural and chemical characterization

Microstructural characterization was performed to elucidate the internal morphology, fiber-matrix interactions, pore distribution, and interfacial bonding within the Styrofoam-coconut coir fiber composites. Consequently, this analysis is fundamental for establishing a direct correlation between the structural architecture of the composites and their resulting acoustic and mechanical performance.

Microstructural characterization. Fig. 7 SEM photographs show that composites with a fiber volume fraction of 5% are very rich in matrix but poor in fiber.

The matrix surface appears smooth and non-porous, resulting in a poor sound absorption coefficient. Similarly, the Styrofoam matrix is very ductile, making it impossible to test its bending strength.

Fig. 8 shows that the matrix and fiber bonds are generally excellent, resulting in very good strength and, bending modulus. There are also pores and gaps between the fibers, including the fibers themselves, which act as sound absorbers.

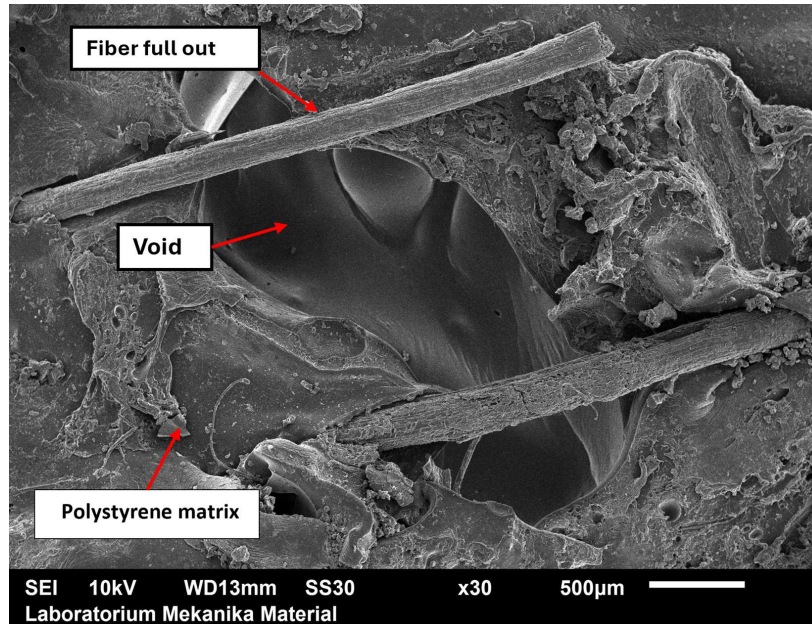


Fig. 7. Scanning electron microscope photo of Styrofoam-5% coconut coir composite

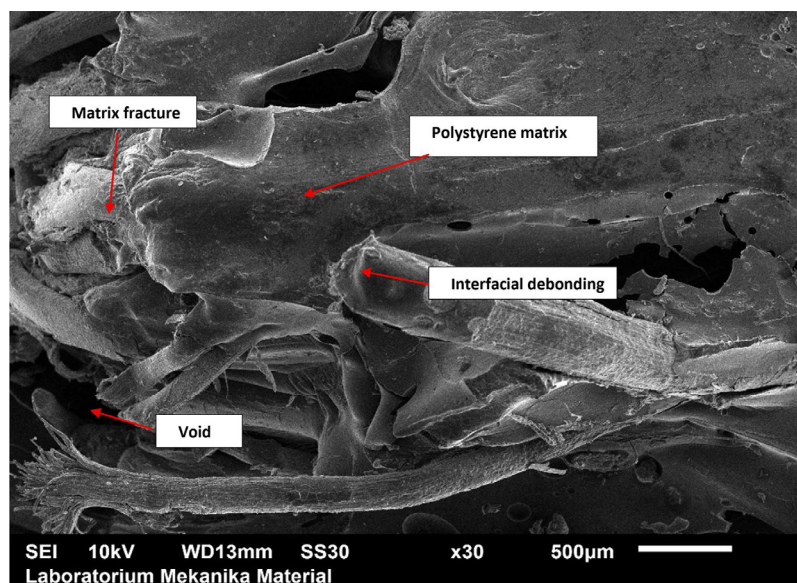


Fig. 8. Scanning electron microscope photo of Styrofoam-30% coconut coir composite

The voids are clearly visible in Fig. 9, showing that not all fibers can be bound by the matrix, resulting in weaker bending strength than the composite with 30% fiber volume fraction. However, this shortcoming gives the composite better sound absorption capabilities.

Similar to the composite with a 40% fiber fraction, the interfacial bonding between the matrix and fibers is relatively weak, as not all fibers are adequately bound by the matrix. This condition leads to the formation of numerous voids, some of which may extend through the composite structure (Fig. 10). As a result, the composite exhibits lower mechanical strength and bending modulus, although it demonstrates a relatively good sound absorption coefficient.

Chemical characterization. Fourier transform infrared (FTIR) spectroscopy was used to analyze the chemical structure and specifically identify the functional groups present in the Styrofoam-coconut fiber composite. This analysis is important for determining the nature of the interaction between

the polymer matrix and the natural fibers, particularly to ascertain whether the composite is dominated by chemical bonds or physical interactions. The FTIR spectrum provides important information regarding the characteristic bands associated with molecular vibrations – such as those involving O–H, C–H, C=O, and C–O groups – which are commonly found in lignocellulosic fibers and polystyrene-based materials. The spectra obtained for composites with varying fiber weight fractions (5%, 20%, 40%, and 60%) are presented in Fig. 11, which shows the presence of characteristic functional groups originating from the polystyrene matrix and lignocellulosic coconut fiber.

At a fiber weight fraction of 5% (Fig. 11, a), the broad absorption band at 3359 cm^{-1} corresponds to the O–H stretching vibration, indicating the presence of cellulose hydroxyl groups and absorbed moisture. Peaks between 2938 and 2886 cm^{-1} are associated with aliphatic C–H stretching, while the bands at 1654 cm^{-1} and 1600 cm^{-1} represent the C=O and aromatic C=C stretching of the polystyrene structure, respectively.

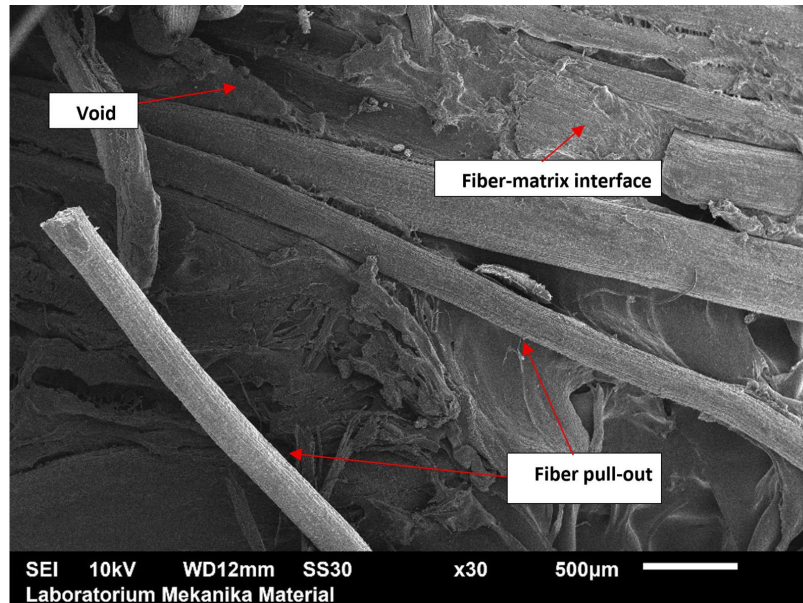


Fig. 9. Scanning electron microscope photo of Styrofoam-40% coconut coir fibers composite

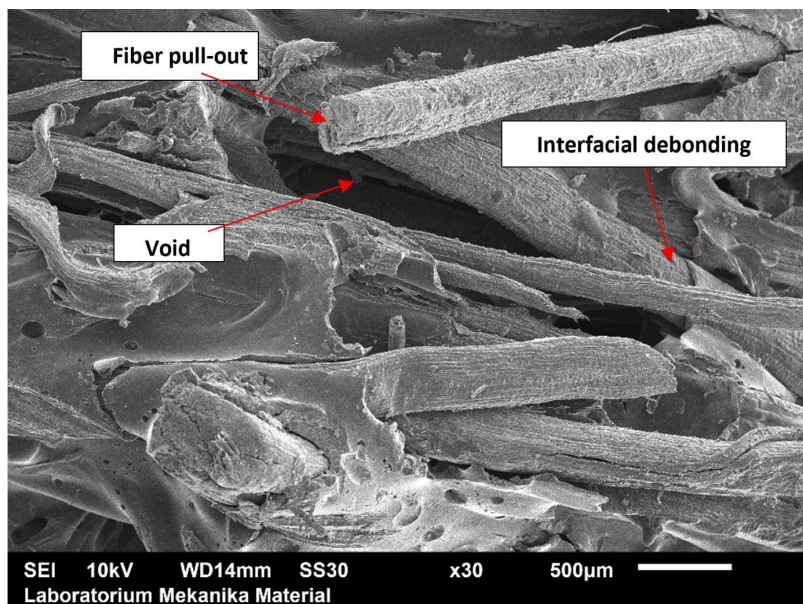


Fig. 10. Scanning electron microscope photo of Styrofoam-60% coconut coir fibers composite

Additionally, the C–O–C stretching vibrations at $1043\text{--}993\text{ cm}^{-1}$ confirm the presence of cellulose and hemicellulose.

At a fiber content of 20% (Fig. 11, *b*), the increased intensity of the O–H and C–O peaks reflects a greater contribution from lignocellulose. Concurrently, a new band near 2339 cm^{-1} indicates absorbed CO_2 or weak triple-bond vibrations. Despite these changes, the persistent aromatic C=C peaks confirm that the polystyrene backbone remains structurally intact.

At a fiber fraction of 40% (Fig. 11, *c*), functional groups derived from the fibers, particularly O–H and C–O, dominate the spectrum. These intense bands indicate increased fiber-matrix interactions. However, the unchanged peak positions suggest that interfacial adhesion depends on physical mechanisms – such as hydrogen bonding and van der Waals forces – rather than new covalent bonds.

At a 60% fiber content (Fig. 11, *d*), stronger hydroxyl absorption and a complex band pattern indicate increased structural heterogeneity. This suggests that excessive fiber content leads to insufficient matrix coverage and weakened interfacial bonding, consistent with the observed degradation of mechanical properties.

Overall, the absence of new FTIR absorption peaks confirms that no chemical reactions occurred during composite formation; the Styrofoam-coconut fiber interactions remain largely physical in nature. SEM observations (Fig. 7–10) support this conclusion, revealing specific interfacial bonding characteristics and pore formation that explain the trade-off between acoustic performance and mechanical strength. Ultimately, the hydroxyl-rich fiber surface enhances sound absorption through internal friction and energy dissipation, while inadequate matrix bonding at higher fiber fractions compromises mechanical integrity.

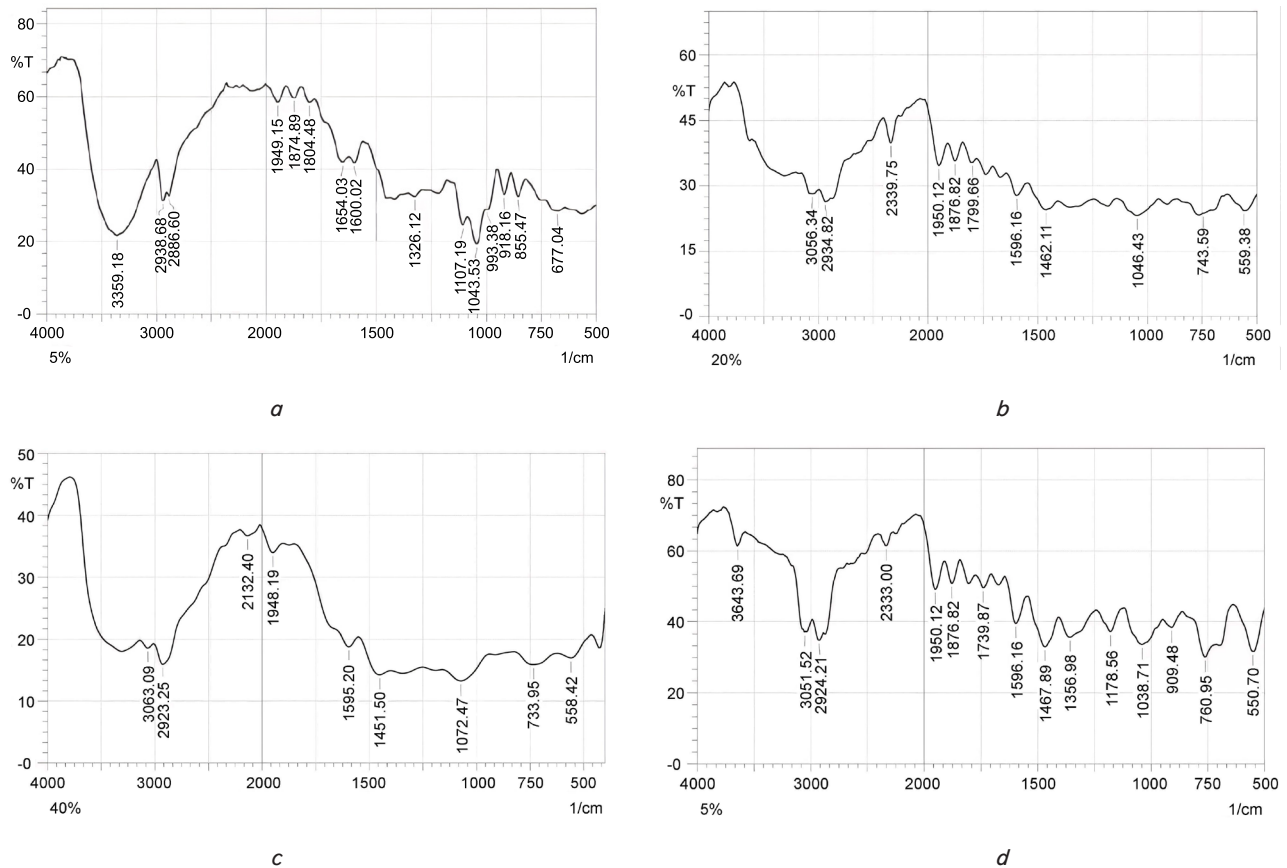


Fig. 11. Fourier transform infrared (FTIR) spectra of Styrofoam-coconut fiber composites: *a* – 5% fiber; *b* – 20% fiber; *c* – 40% fiber; *d* – 60% fiber

6. Discussion of the results of sound absorption, mechanical, microstructural and chemical characterization

As demonstrated in Table 1, an EPS-to-solvent ratio of 1:3 yielded the most homogeneous matrix, reflecting efficient polymer dissolution and enhanced workability during composite fabrication. Deviations from this ratio proved detrimental: an insufficient solvent concentration caused incomplete dissolution, resulting in an uneven matrix and localized agglomeration, whereas excessive solvent addition prolonged evaporation times and reduced processing efficiency. Consequently, the pronounced homogeneity achieved at the 1:3 ratio signifies a highly effective interaction between the solvent molecules and the EPS polymer chains, thereby facilitating superior matrix continuity and uniform fiber distribution. Ultimately, establishing this optimal baseline ratio is critical, as matrix homogeneity fundamentally dictates subsequent pore formation, interfacial bond quality, and overall composite performance.

The effect of fiber volume fraction on sound absorption performance is illustrated in Fig. 3, *a*, *b*. In general, the sound absorption coefficient increases with rising frequency and fiber content percentage. Descriptive statistical analysis shows that most composites have an average sound absorption coefficient above 0.2, confirming their suitability as effective sound-absorbing materials. At lower fiber fractions (5–20 vol%), the acoustic response tends to be moderate be-

cause the composite structure is still dominated by the matrix, which inherently limits pore connectivity and obstructs airflow pathways. However, as the fiber content increases, scanning electron microscope (SEM) observations reveal the progressive formation of interconnected pores, hollow fiber lumens, and irregular internal channels. These microstructural characteristics significantly enhance airflow resistance and acoustic energy dissipation. This phenomenon aligns with findings in the literature [15–17], which confirm that porous natural fiber composites dampen sound through mechanisms of viscous friction, thermal dissipation, and double internal reflection within the interconnected pore network. Therefore, the observed statistical trends confirm that increasing the fiber content actively enhances acoustic damping mechanisms, particularly in the mid-to-high frequency range.

As illustrated in Fig. 4, flexural strength increased proportionally with fiber content, reaching a maximum value at 30 vol%. This upward trend demonstrates that the coconut fibers effectively enhance stress transfer within the expanded polystyrene (EPS) matrix. Furthermore, statistical analysis of the flexural data corroborates the 30 vol% fraction as the optimal threshold, representing an ideal balance between reinforcement efficiency and structural continuity. Conversely, when the fiber content exceeded 40 vol%, both the flexural strength and elastic modulus experienced a precipitous decline. The pronounced variability observed at these higher fiber fractions indicates increased structural heterogeneity, which is likely attributable to fiber agglomeration, excessive

void formation, and inadequate matrix wetting. These findings align with existing literature [14], reinforcing the premise that the mechanical performance of polystyrene-based composites is critically dependent on filler dispersion, interfacial adhesion, and overall microstructural uniformity.

SEM analysis was used to investigate how variations in pore morphology and interfacial bonding influenced both acoustic absorption and flexural performance. The micrographs confirm that an increase in the fiber volume fraction progressively increases pore density, void formation, and surface roughness. Crucially, this microstructural evolution exerts a dual effect that is contradictory regarding acoustic and mechanical responses. On one hand, the proliferation of interconnected pores enhances sound absorption through increased airflow tortuosity and the lengthening of the propagation path of incident sound waves, thereby reinforcing viscous and thermal dissipation mechanisms [15–17]. On the other hand, excessive pore formation inherently disrupts matrix continuity and weakens interfacial cohesion, leading to a reduction in flexural strength and elastic modulus [14]. Through the synthesis of acoustic, mechanical, and morphological data, a definitive structure-property relationship for recycled EPS–coconut fiber composites can be established. The overall performance of the composite reaches an optimal point at a fiber fraction of approximately 30 vol%. At this critical threshold, pore connectivity has developed sufficiently to maximize acoustic attenuation, while still maintaining matrix continuity and adequate stress transfer capability. Ultimately, these findings demonstrate that acoustic absorption and mechanical integrity are governed by competing microstructural mechanisms, such that optimal composite performance depends heavily on a precise balance between porosity development and interfacial cohesion.

Several limitations affect the interpretation and practical application of these findings. First, the testing relied on laboratory-scale specimens of constant thickness within a limited frequency range (300–4000 Hz); thus, the performance of full-scale panels under actual service conditions may differ. Second, SEM provides only a qualitative evaluation of pore characteristics, neglecting quantitative analysis of porosity, pore size distribution, and tortuosity. Third, this study does not assess long-term environmental durability against humidity, temperature fluctuations, ultraviolet radiation, and biological degradation. Finally, the evaluation of critical building properties, such as fire resistance and thermal insulation, remains outside the scope of the current study.

Future study should better establish the structure-property relationships of recycled EPS-based acoustic composites. Specifically, quantifying porosity, air flow resistance, and tortuosity will clarify the mechanisms of acoustic attenuation. Assessing long-term durability, moisture resistance, thermal stability, and fire resistance is also crucial for determining suitability for building applications. Furthermore, optimizing fiber treatment and composite architecture can enhance both acoustic and mechanical performance. Ultimately, this investigation will yield the technical data necessary to design and scale up the production of sustainable acoustic panels made from recycled EPS and agricultural waste.

7. Conclusion

1. The optimal solvent-to-Styrofoam ratio was established at 3:1, yielding a homogeneous matrix highly suitable for composite fabrication. This structural uniformity is primarily

driven by the effective dissolution capacity and rapid solidification behavior of the Pertalite gasoline solvent.

2. Furthermore, the resulting composites demonstrated exceptional sound absorption capabilities, particularly within the high-frequency range (2000–4000 Hz), achieving a maximum absorption coefficient of 0.91. This enhanced acoustic attenuation is directly attributed to the inherent porous structure and internal cavities of the coconut coir fibers.

3. In terms of composition, a fiber volume fraction of 30% emerged as the optimal threshold. At this fraction, the material achieved an ideal balance between mechanical strength and acoustic performance, a synergy facilitated by enhanced fiber-matrix interactions and superior structural integrity.

4. Microstructural analysis established a clear structure-property relationship in the composites. The development of interconnected pores and voids enhanced acoustic attenuation, whereas excessive porosity reduced flexural performance due to lower matrix continuity and weaker fiber-matrix interactions.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

Funding

The study was supported by LPPM Universitas Udayana (Institute for Research and Community Service Udayana University).

Data availability

The data will be made available upon reasonable request.

Use of artificial intelligence

Artificial intelligence tools (ChatGPT, GPT-5.3, OpenAI) were used in the preparation of this manuscript, specifically for language editing and structural refinement (Sections 1–6). AI was used to improve the clarity, grammatical correctness, and logical flow of the manuscript. All scientific content, data interpretations, and conclusions have been verified and validated by the authors. The use of AI tools did not influence the scientific results or research conclusions.

Authors' contributions

I Ketut Gede Sugita: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft; **Ngakan Putu Gede Suardana:** Supervision, Validation, Writing – review & editing, Project administration; **Jefri S. Bale:** Investigation, Data curation; **Cipk Kencanawati:** Formal analysis, Visualization; **I Putu Lokantara:** Methodology, Validation.

References

1. Curiac, A. S., Petre, A., Stoica, A., Sandu, S. (2017). Preparation of adhesives from the expandable polystyrene waste. *Journal of Young Scientist*, V. Available at: https://journalofyoungscientist.usamv.ro/pdf/vol_V_2017/Art3.pdf
2. A Global Call for Climate Action. Available at: <https://www.un.org/it/node/71013>
3. Seghiri, M., Boutoutaou, D., Kriker, A., Hachani, M. I. (2017). The Possibility of Making a Composite Material from Waste Plastic. *Energy Procedia*, 119, 163–169. <https://doi.org/10.1016/j.egypro.2017.07.065>
4. Brahmakumar, M., Pavithran, C., Pillai, R. (2005). Coconut fibre reinforced polyethylene composites: effect of natural waxy surface layer of the fibre on fibre/matrix interfacial bonding and strength of composites. *Composites Science and Technology*, 65 (3-4), 563–569. <https://doi.org/10.1016/j.compscitech.2004.09.020>
5. Suardana, N. P. G., Sugita, I. K. G., Wardana, I. G. N. (2020). Hybrid acoustic panel: the effect of fiber volume fraction and panel thickness. *Materials Physics and Mechanics*, 44 (1), 77–82. https://dx.doi.org/10.18720/MPM.4412020_9
6. Moreno, A., Lejnieks, J., Galià, M., Lligadas, G., Percec, V. (2018). Acetone: a solvent or a reagent depending on the addition order in SET-LRP. *Polymer Chemistry*, 9 (45), 5411–5417. <https://doi.org/10.1039/c8py01331d>
7. Garcia, M. T., Gracia, I., Duque, G., Lucas, A. d., Rodríguez, J. F. (2009). Study of the solubility and stability of polystyrene wastes in a dissolution recycling process. *Waste Management*, 29 (6), 1814–1818. <https://doi.org/10.1016/j.wasman.2009.01.001>
8. Allard, J. F., Atalla, N. (2009). *Propagation of Sound in Porous Media*. John Wiley & Sons. <https://doi.org/10.1002/9780470747339>
9. Asdrubali, F., Schiavoni, S., Horoshenkov, K. V. (2012). A Review of Sustainable Materials for Acoustic Applications. *Building Acoustics*, 19 (4), 283–311. <https://doi.org/10.1260/1351-010x.19.4.283>
10. Yang, H.-S., Kim, D.-J., Kim, H.-J. (2003). Rice straw-wood particle composite for sound absorbing wooden construction materials. *Bioresource Technology*, 86 (2), 117–121. [https://doi.org/10.1016/s0960-8524\(02\)00163-3](https://doi.org/10.1016/s0960-8524(02)00163-3)
11. Bai, P., Yang, X., Shen, X., Zhang, X., Li, Z., Yin, Q. et al. (2019). Sound absorption performance of the acoustic absorber fabricated by compression and microperforation of the porous metal. *Materials & Design*, 167, 107637. <https://doi.org/10.1016/j.matdes.2019.107637>
12. Venegas, R., Zieliński, T. G., Núñez, G., Bécot, F.-X. (2021). Acoustics of porous composites. *Composites Part B: Engineering*, 220, 109006. <https://doi.org/10.1016/j.compositesb.2021.109006>
13. Zaafarani, N. N., Nour, M., El-Kassas, A. M., Elsheikh, A. (2023). A new recycled high-impact polystyrene-rice straw composite: eco-friendly fabrication and characterization. *International Journal of Environmental Science and Technology*, 21 (2), 1193–1202. <https://doi.org/10.1007/s13762-023-05039-9>
14. Karaoui, M., Hsissou, R., Alami, M., Assouag, M. (2023). Thermal, flow, and mechanical properties of composites based on polystyrene (PS) and snail shell powder (SSP) biofiller (PS/SSP). *Iranian Polymer Journal*, 32 (5), 621–631. <https://doi.org/10.1007/s13726-023-01151-2>
15. Zhang, J., Shen, Y., Jiang, B., Li, Y. (2018). Sound Absorption Characterization of Natural Materials and Sandwich Structure Composites. *Aerospace*, 5 (3), 75. <https://doi.org/10.3390/aerospace5030075>
16. Hassan, T., Jamshaid, H., Mishra, R., Khan, M. Q., Petru, M., Novak, J. et al. (2020). Acoustic, Mechanical and Thermal Properties of Green Composites Reinforced with Natural Fibers Waste. *Polymers*, 12 (3), 654. <https://doi.org/10.3390/polym12030654>
17. Hou, Z., Ma, X., Pan, L., Zhang, R., Wang, L. (2024). Study on the sound absorption characteristics and noise reduction mechanism of coconut-shell-activated carbon particles and coconut fiber composite biomass sound-absorption materials. *Materials Research Express*, 11 (11), 115603. <https://doi.org/10.1088/2053-1591/ad923f>
18. Suardana, N. P. G., Lokantara, I. P., Lim, J. K. (2011). Influence of water absorption on mechanical properties of coconut coir fiber/poly-lactic acid biocomposites. *Materials Physics and Mechanics*, 12 (2), 113–125. Available at: https://www.researchgate.net/publication/268267847_Influence_of_water_absorption_on_mechanical_properties_of_coconut_coir_FiberPolyLactic_acid_biocomposites
19. ASTM E1050-98. Standard Test Method for Impedance and Absorption of Acoustical Materials Using a Tube, Two Microphones, and a Digital Frequency Analysis System (1998). ASTM International.
20. Rusli, M., Nanda, R. S., Dahlan, H., Bur, M., Okuma, M. (2021). Sound Absorption Characteristics of Composite Panel Made from Coconut Coir and Oil Palm Empty Fruit Bunches Fibre with Polyester. *International Journal of Automotive and Mechanical Engineering*, 18 (3), 9022–9028. <https://doi.org/10.15282/ijame.18.3.2021.14.0691>
21. ASTM D790-25. Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials. ASTM International. <http://doi.org/10.1520/D0790-25>
22. Sun, W., Pan, B., Song, X., Xiao, H., Zhou, J., Sui, D. (2022). A novel sound absorber design of nanofibrous composite porous material. *Materials & Design*, 214, 110418. <https://doi.org/10.1016/j.matdes.2022.110418>
23. Hosseini, M., H., M., Ghassem, M., Shamel, M., Yeng, S., Yi, S., Zong, P., Mohd Nor, M. J. (2013). Utilizing Malaysian Natural Fibers as Sound Absorber. Modeling and Measurement Methods for Acoustic Waves and for Acoustic Microdevices. <https://doi.org/10.5772/53197>
24. Kiran, M. C., Mamatha, B. S., Anand, N., Prakash, V., Murthy, N. (2019). Efficiency of Coir Particle Board for Acoustic & Thermal Applications. *Open Journal of Acoustics*, 09 (03), 39–47. <https://doi.org/10.4236/oja.2019.93004>
25. Chin Vui Sheng, D. D., Yahya, M. N. B., Che Din, N. B. (2020). Sound Absorption of Microperforated Panel Made from Coconut Fiber and Polylactic Acid Composite. *Journal of Natural Fibers*, 19 (7), 2719–2729. <https://doi.org/10.1080/15440478.2020.1821290>
26. Mohammed, A., Rao, D. N. (2023). Investigation on mechanical properties of flax fiber/expanded polystyrene waste composites. *Heliyon*, 9 (3), e13310. <https://doi.org/10.1016/j.heliyon.2023.e13310>