

Acoustic Panel from Coconut Fiber and Spent Coffee Ground as Sound-Absorbing Material for Sustainability

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Abstract - Conventional building materials are energy-intensive and generate substantial waste, motivating the valorization of agricultural by products into sustainable acoustic materials. This study developed an acoustic panel from Coconut Fiber (CF) and Spent Coffee Grounds (SCG) bound with a cassava starch-based adhesive, with SCG incorporated at 0%, 15%, and 30% (samples A1, A2, and A3, respectively). SCG addition increased panel density from 208.9 kg/m³ (A1) to 247.5 and 268.7 kg/m³ for A2 and A3. Tensile testing showed that SCG reduced the maximum stress while increasing the Young's modulus, indicating a trade-off between ductility and stiffness. Scanning electron microscopy revealed that SCG particles bridged the coconut fiber network, altering the pore structure and air-flow resistivity. Sound absorption coefficients measured across 250-5000 Hz using the impedance tube method showed that A2 (85% CF, 15% SCG) achieved the best overall performance, reaching coefficients of 0.86 at 500 Hz and 0.69 at 250 Hz and outperforming A1 and A3, particularly at low-to-mid frequencies. Excessive SCG in A3 reduced absorption due to increased density and reduced porosity. These findings demonstrate that CF-SCG composite panels are a promising, low-cost, biobased alternative to conventional acoustic materials and SCG for balancing sound absorption performance with sustainable resource valorization.

Keywords - Acoustic Panel, Biowaste, Sound Absorbing, Sound Damping, Sustainable.

INTRODUCTION

Conventional building materials like steel, concrete and synthetic insulation require a lot of energy to produce and produce a lot of trash, which contributes to resource depletion and climate change [1]. Sustainable building materials are therefore expected to reduce environmental pressure from the usage of conventional construction practices, which account for nearly 40% of global carbon emissions [2]. The increased demand for sustainable building materials has motivated innovation in valorizing agricultural by-products into high value and eco-friendly solutions. Valorizing agricultural by-products also supports the circular economy paradigm advocating the reuse or repurposing waste streams into functional materials. Further, recent study predicted the reduction of embodied

carbon by 50% by the usage of renewable, recycled or bio-based feedstocks [3]. Innovations on building materials include low-carbon concrete [4], biodegradable insulation [5], lightweight structural panels [6] and acoustic panels [7].

Research on biobased acoustic panels has been extensively conducted. Biobased acoustic panels take advantage of the natural fibrous and porous structure of biomass materials to trap and dissipate sound waves. They reduce sound energy by leveraging their inherent porosity, which promotes viscous friction and thermal dissipation as sound waves propagate through materials. This will minimize reflection and reverberation, and thus providing sound absorption [8]. Natural fibers that have been investigated extensively include hemp fiber [9], coconut fiber [10], rice fiber [11] and kenaf

fiber [12]. Although studies have been conducted, scalability and performance optimization remain challenges, necessitating interdisciplinary research to enhance durability, acoustic-thermal properties and cost-effectiveness.

The vast availability of coconut fibers (CF) holds significant promise as cost effective and sustainable materials for acoustic panels. CF exhibits sound absorption mechanisms through viscous air friction and thermal energy dissipation, particularly effective at mid-to-high frequencies. At low frequencies, coconut fibers are less effective in absorbing sound, a major challenge for design engineers and architects [13]. Therefore, improving the low-frequency sound absorption of CF-based panels while maintaining the porous structure required for effective sound-energy dissipation remains an important challenge.

Previous studies have demonstrated the potential of coconut fiber and other agricultural residues as sustainable-absorbing materials [9-11]. Combining coir fiber with granular rice husk can [12] improve acoustic performance, supporting the potential of fibro-granular structures for overcoming the relatively poor low-frequency absorption of single natural-fiber systems. Their coir fiber-rice husk panels achieved a noise reduction coefficient of 0.76. This demonstrates the incorporation of granular biomass into a fibrous network can provide favorable acoustic performance [13]. Beyond material composition, the acoustic response of porous bio-based materials is strongly governed by their physical and microstructural characteristics. Density and thickness alone do not determine sound absorption. Porosity, fiber dimensions and airflow resistivity also control the penetration and dissipation of acoustic energy within the materials [14]. This indicates that introducing particulate biomass into a fibrous matrix may alter acoustic performance by modifying the internal pore network and resistance to airflow.

In parallel, coffee-derived residues have shown potential as acoustic materials. A spent coffee ground (SCG)-starch composite for non-load-bearing building applications showed to have sound absorption comparable to conventional materials [15]. Favorable sound absorption from coffee-waste based building composites was associated with their porous structure [16]. However, despite these findings, the incorporation of SCG as a granular component within a coconut-fiber network has received limited attention.

In this study, we designed an acoustic panel from coconut fiber and spent coffee grounds (SCG). SCG was incorporated into the CF network to modify the panel density and internal structure, which may influence sound-wave propagation and energy dissipation. By compositing coconut fiber with SCG, we expected to obtain an acoustic panel with improved sound absorption across a wide range of frequencies, particularly addressing the limited low-frequency absorption of CF. Therefore, this study aimed to investigate the effect of SCG content on the density, mechanical properties, microstructure and sound absorption of CF-based acoustic panels and to determine the composition providing the best overall acoustic performance.

METHODS

Materials

CF and SCG, the main component of acoustic panel, were obtained from domestic market and household waste. CF was cut into ± 3 cm, washed with distilled water to remove impurities, and subsequently dried in oven. Meanwhile, SCG was washed and dried at 60 °C to reduce its moisture content, then ground into 100 mesh to enhance its bonding capability within the panel structure. Commercial cassava was used as the binder.

Methods

Panel Fabrication

A composition-controlled experimental design was used to investigate the effect of SCG incorporation on the physicomechanical and acoustic properties of CF-based panels. Three CF:SCG compositions were prepared: 100:0 (A1), 85:15 (A2), and 70:30 (A3), while the binder formulation, molding procedure, panel dimensions and drying conditions were maintained consistently across all formulations. The resulting panels were subsequently compared in terms of density, mechanical properties, morphology and sound absorption coefficient.

Acoustic panel was fabricated by mixing CF and SCG followed by binding them with natural-based adhesive. The binder solution was prepared from cassava starch, glycerin and distilled water. Acoustic panel was molded with the dimension of 23 cm in length and 18 cm in width. Initially, the CF and SCG were mixed thoroughly. Subsequently, the bio-based binder solution was added gradually while kneading the mixture until a homogenous and compact dough-like texture was obtained. This step ensured that the material could be flattened and compressed

uniformly within the mold. Next, the mixture was subjected to drying and heating in an oven at 70 °C for 24 hours to reduce the moisture content and enhance the mechanical integrity of the panel. To evaluate the effect of SCG composition on the performance of the acoustic panel, several composition variations were prepared (table 1).

Table 1. Composition of acoustic panel

Sample code	Coconut fiber (%)	Spent coffee ground (%)
A1	100	0
A2	85	15
A3	70	30

Mechanical Testing

The mechanical performance of acoustic panel was evaluated through its stress-strain characteristics obtained from tensile testing using the Universal Testing Machine (UTM 500 FL). The stiffness and the Young's modulus (E) of the acoustic panel was determined based on Hooke's Law, which describes the linear relationship between stress and strain within the elastic deformation region of a material. The modulus is calculated using the equation (1).

$$E = \frac{\sigma}{\varepsilon} \quad (1)$$

σ represents the applied stress (force per unit area), and ε is the resulting strain (relative deformation). This relation assumes that the material behaves elastically and returns to its original shape upon removal of the applied load. The slope of the initial linear region of the curve represents the Young's modulus.

Morphological Characterization

Morphological analysis was carried out using a Thermo Scientific Prisma E Scanning Electron Microscope (SEM) to investigate the porosity formed in the acoustic panel.

Acoustic Absorption Coefficient

The fabricated acoustic panels were subjected to acoustic testing to determine their sound absorption coefficient (α) across a frequency range of 250–5000 Hz, covering low, mid and high frequencies. This evaluation aimed to assess the effectiveness of incorporating SCG in improving the panel's sound-damping performance, particularly in low-frequency absorption. The sound absorption coefficient (α) and surface impedance were measured using the Kundt tube method (PASCO Resonance Tube WA-9612), in accordance with the EN ISO 10534-2 standard.

The coefficient α was calculated based on the reflection coefficient g , following the equation (2).

$$\alpha = 1 - g \quad (2)$$

Where g is obtained from (3).

$$g = \left(\frac{V_{max} - V_{min}}{V_{max} + V_{min}} \right)^2 \quad (3)$$

Where V_{max} and V_{min} represent the maximum and minimum electric voltages measured at the terminals of the same microphone.

RESULTS AND DISCUSSION

Mechanical Properties

The fabricated acoustic panel without SCG has a density of 208.9 kg/m³ while the addition of SCG improve the density of the panels. We obtained the density at 247.5 and 268.7 kg/m³ for acoustic panels with the ratio of CF:SCG at 85:15 and 70:30, respectively. The findings indicate that slight addition of SCG improves the density of the Acoustic panel. In this research, acoustic panel occurs as composite consisting of CF, SCG and slight amount of starch as the binder. Other study showed that the composite consists of SCG and starch only at ratio of 2:1 had the density of 588 kg/m³, almost triple the acoustic panel [13]. The acoustic panels can be classified as high-density acoustic panel with the density ranged from 208.9 – 268.7 kg/m³ (table 2) High-density materials may enhance the panel ability to absorb sound. This is possibly due to the characteristic of high-density materials that can slow down the sound propagation, increase the friction, and improve the energy dissipation as heat. However, density alone does not determine sound absorption. The acoustic behaviour of natural-fiber materials is also strongly influenced by porosity, pore tortuosity, fiber dimensions, thickness and air flow resistivity [16]. Increasing density may enhance energy dissipation only when sufficient interconnected pores remain available for sound waves to penetrate the material.

Table 2. Density of sample

Sample code	Density (kg/m ³)
A1	208.9
A2	247.5
A3	268.7

Further, the addition of SCG (Sample A2 and A3) to the panel increases the density. Varied density along

with the Acoustic panel composition indicates the possibility to tailor the acoustic properties of the panel, providing advantage for specialized acoustic applications.

The addition of SCG not only influence the acoustic performance, but it also affects the mechanical properties of the panel. The addition of SCG decrease the maximum stress of the acoustic panel (Figure 1a), indicating an improve of panel ductility along with the addition of SCG. This ductility may improve acoustic performance by enabling microstructural deformation under sound waves, enhancing energy dissipation. Figure 1b showed that the Young's Modulus of the acoustic panel increase with the addition of SCG. Young's modulus indicates the stiffness of materials. The increase in modulus suggests that SCG incorporation altered the interaction and packing within the CF–starch network, producing a stiffer composite structure.

The stiffness may affect how sound interacts with the material. High stiffness could influence the panel's ability to vibrate or deform when sound hits

it, which in turn affects sound absorption. If a material is too stiff, maybe it does not allow enough vibration or movement to dissipate the sound energy effectively. The relationship between mechanical properties and acoustic absorption, however, is not independent of microstructure. Previous studies have demonstrated that the acoustic behavior of porous bio-based materials results from the combined effects of mechanical characteristics, porosity, density and airflow resistance rather than stiffness alone.

Therefore, it is likely that for acoustic panel applications, materials with lower Young's Modulus are preferable. However, structural applications might require stiffness. Therefore, lower Young's Modulus does not a primary indicator for the success of acoustic panel. We observed that acoustic panel with the addition of SCG (A2 and A3) has higher Young's Modulus compared to that of acoustic panel without SCG (sample A1). However, data on acoustic absorption coefficient (table 3) indicates that all tested samples are considered meet the acoustic requirement according to ISO 354:203.

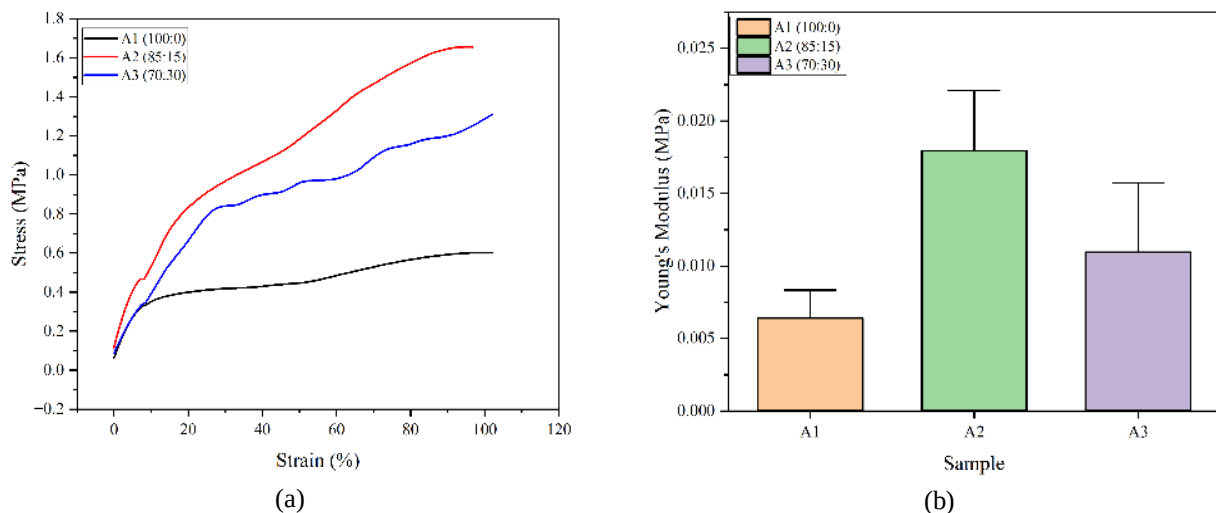


Figure 1. (a) Graphic of Strain-Stress and (b) Young's Modulus for Each Sample

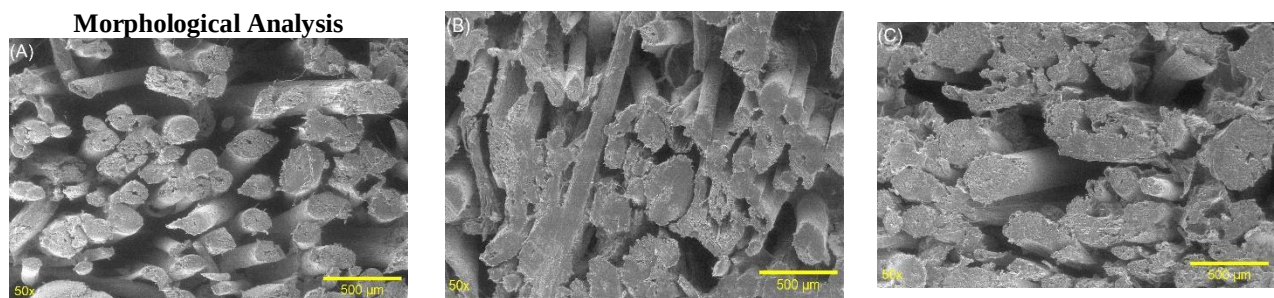


Figure 2. SEM images of the cross-sectional microstructure of (A) A1, (B) A2, and (C) A3

Figure 2 showed the cross sectional microstructures of the acoustic panels. A1 consisted of a relatively open, loose network of fibers with large interstitial pores. With these conditions, air flows to freely through the materials, leading to low air resistivity. The presence of SCG in the acoustic panels would bridge the space between fibers as indicated in Figure 2B. The SCG particles seem to be distributed throughout the fiber network. With this microstructure, the internal microstructure of sample A2 provide the friction leading to enhanced the sound absorption. Having the highest SCG, sample A3 showed the most dense microstructure with heavy agglomeration, providing excessive high air flow resistivity. The high SCG particle caused the sound waves to be reflected. For maximum absorption, the material's impedance must be close to the impedance of the surrounding air. The presence of dense particles cause the sound sees the panel structure as wall rather than porous materials, causing the low absorption coefficient.

This phenomenon suggests that for acoustic panel, the presence of porosity may alter the mechanical properties, thus the performance of acoustic panel may not only be determined by the Young's Modulus. Further, Young's Modulus in acoustic panel may enhance structural durability. Therefore, the dual presence of CF and SCG in Acoustic panel not only provide good acoustic performance but also enhance the structural durability.

Acoustic Absorption Coefficient

The acoustic performance of the acoustic panel was evaluated based on its sound absorption coefficient across different frequencies (250–5000 Hz). Sound absorption coefficient was calculated using equation (2). The calculation (table 3) showed that the composition of the panel determined the sound absorption coefficient. Comparing the sound absorption coefficient of sample A1 with A2 and A3,

the inclusion of SCG influences the material's sound absorption performance across different frequency ranges.

Table 3. Sound Absorption Coefficient Towards Frequency for Each Sample

Frequency (Hz)	Sound Absorption Coefficient		
	A1	A2	A3
250	0.40	0.69	0.04
500	0.67	0.86	0.64
1000	0.51	0.88	0.11
2000	0.78	0.77	0.65
2500	0.91	0.76	0.64
5000	0.67	0.69	0.60

Sample A1, composed solely of CF, exhibited strong absorption particularly in the mid-to-high frequency range, with the highest coefficient (α) reaching 0.91 at 2500 Hz. However, its performance at lower frequencies (250 Hz) was relatively limited ($\alpha = 0.40$). This behavior agrees with previous observations that natural fibrous absorbers generally perform well at medium and high frequencies but often exhibit limited low-frequency absorption [14]. Sample A2 which incorporated 15% SCG, demonstrated enhanced absorption across the entire frequency range, particularly at 500 Hz ($\alpha = 0.86$) and 250 Hz ($\alpha = 0.69$). This suggests that the addition of SCG up to 15% can synergize with CF to improve low-frequency sound absorption, likely due to increased material porosity and density balance [13]. The improvement is consistent with the SEM observations, in which SCG partially occupied and bridged the spaces between CF while retaining an interconnected porous structure. Rather than density alone, this combination of increased density and modified pore architecture may provide a more favorable resistance to airflow and a more tortuous pathway for sound propagation, increasing opportunities for viscous and frictional energy dissipation.

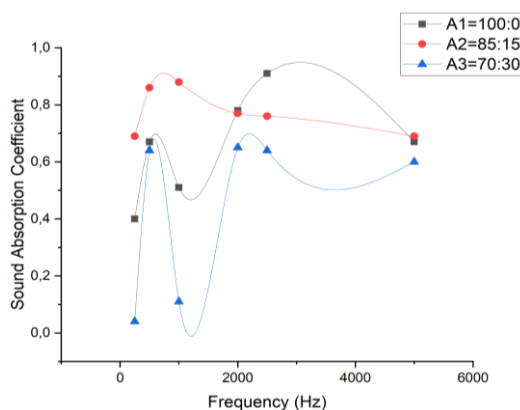


Figure 3. Graphic of Sound Absorption Coefficient Towards Frequency for Each Sample

Sample A3, containing 30% SCG, showed reduced absorption performance overall, particularly in low frequencies ($\alpha = 0.04$ at 250 Hz and $\alpha = 0.11$ at 1000 Hz). The excessive SCG content may have led to denser and less porous panel structures, thereby reducing the material's ability to trap and dissipate sound energy. This result shows that the relationship between SCG content and acoustic absorption is not linear. Although A3 had the highest density (268.7 kg/m³), it did not provide the highest sound absorption. The SEM image of A3 shows greater particle accumulation and a denser structure, supporting the interpretation that excessive SCG loading can restrict the pore network required for effective sound penetration and dissipation. This finding further demonstrates that an optimum balance among density, porosity and airflow resistance is more important than maximizing density alone.

When compared to commercial acoustic panels, which generally exhibit absorption coefficients (α) ranging between 0.6–0.9 in mid and high frequencies, both A1 and A2 demonstrate comparable effectiveness. According to the Indonesian National Standard (SNI 03-6389-2000) on sound-absorbing materials, a coefficient above 0.50 is considered satisfactory for general room acoustic applications. Both A1 and A2 exceed this value across several frequencies, indicating their potential for practical use in noise control applications such as studios, offices, or multipurpose halls. Overall, A2 (85% CF + 15% SCG) offers the best balance between material sustainability and acoustic performance, outperforming the other samples in wide frequency absorption, particularly in low-to-mid frequency ranges.

CONCLUSION

The development of the acoustic panel demonstrates a promising innovation in sustainable building materials by utilizing agro-industrial waste, coconut fiber (CF) and spent coffee grounds (SCG). This acoustic panel shows good sound absorption performance across a wide range of frequencies. This was enabled through varying the ratio of CF to SCG therefore suitable for diverse acoustic applications. The mechanical property testing showed high-density acoustic panel that has high ductility and Young's Modulus. Combinations of them may enable microstructural deformation under sound waves, enhancing energy dissipation, thus enhancing the acoustic performance. In addition to

its acoustic functionality, this acoustic panel contributes to environmental sustainability through its biobased composition, aligning with circular economy principles by recycling and upcycling agricultural waste into functional materials. Its ability to serve as both an effective noise-damping element and a customizable interior design component enhances its practical value in sustainable architecture.

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