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Acoustic characterization of Abaca Wool as a natural sound absorber: experimental and simulation approach

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Abstract

The increasing environmental and health concerns associated with synthetic sound-absorbing materials such as rockwool and fiberglass—due to their non-biodegradable nature and potential respiratory hazards—have prompted the exploration of sustainable alternatives. This study introduces *Abaca-wool*, a bio-based acoustic material derived from abaca banana fibers (*Musa textilis*) engineered to mimic the structure of mineral wool. The research aimed to evaluate the acoustic performance of Abaca-wool through both experimental measurements and numerical simulations, while examining the influence of fiber morphology on sound absorption. The fabrication process involved alkaline treatment with 15% NaOH, followed by sequential wet and dry refining to produce a randomly entangled, porous structure. Microscopic analysis revealed micro-diameter fibers and high porosity (~93%), which are critical for enhancing viscoelastic interactions between air particles and fiber walls. Key physical parameters—density and airflow resistivity (64.117 kPa·s/m²)—were measured to support numerical modeling using AFMG SoundFlow. Experimental results using the two-microphone impedance tube method showed high absorption coefficients, peaking at 0.89 at high frequencies and 0.83 at around 1000 Hz. The observed performance is attributed to optimized fiber morphology, which facilitates energy dissipation through friction and acoustic scattering. Numerical simulations exhibited good agreement with experimental data, with minor deviations linked to the homogeneous assumptions in the model. Overall, Abaca-wool demonstrates excellent potential as a biodegradable, low-density, and high-performance acoustic material, offering a viable and environmentally responsible alternative to conventional synthetic absorbers.

Keywords: Abaca-wool; AFMG soundflow; density; sound absorption coefficient; porous material

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INTRODUCTION

Sound-absorbing materials play a crucial role in controlling noise levels and enhancing acoustic quality in a variety of spaces, ranging from commercial and residential buildings to industrial environments. Generally, these materials function by dissipating the energy of incident sound waves through conversion into heat and vibrations within their porous or fibrous internal structure. The effectiveness of sound absorbers is typically quantified using the sound absorption coefficient, which depends on the material's physical characteristics and the frequency of the sound waves.

Over the past few decades, synthetic fiber-based materials such as rockwool and fiberglass have dominated acoustic applications due to their high sound absorption capacity, dimensional stability, and commercial availability. However, the use of these synthetic materials raises significant environmental and health concerns (Asdrubali et al., 2015). From an ecological perspective, their production processes are energy-intensive and contribute to substantial carbon emissions. Additionally, their waste is non-biodegradable and poses long-term pollution risks. From a health standpoint, the fine particles released from fiberglass and rockwool can cause skin irritation and respiratory issues upon prolonged exposure (Chen & Zhang, 2018).

These limitations have led to growing interest in the development of alternative sound-absorbing materials that are both environmentally friendly and safe for human use. One emerging approach involves the utilization of natural fibers as the base material for acoustic composites. Numerous studies have demonstrated that natural fibers—such as coconut husk, kenaf, hemp, and pineapple leaves—possess promising acoustic properties due to their fibrous microstructure, low density, and local availability (Fatima & Mohanty, 2011; Zulkifli et al., 2010)

Figure 1. Natural Abaca Fibers.

In this context, abaca (*Musa textilis*) fibers, as illustrated in Figure 1, have emerged as a promising yet underexplored candidate for acoustic applications. Abaca (Musa textilis Nee), a member of the Musaceae family, resembles the common banana plant but produces inedible fruit and yields high-quality natural fiber from its stalk. Originating from the Philippines, abaca was introduced to Ecuador during World War II(Jiménez et al., 2005). In Southeast Asia, particularly in the Philippines, abaca has long been integrated into traditional agricultural systems and is typically planted as a third-stage crop following the clearing and burning of forested land, which results in decreased soil fertility (Lacuna-Richman, 2002).

The abaca plant grows to a height of 3 to 4 meters, with a stem diameter ranging from 15 to 38 cm, and produces approximately 7 to 9 leaves (Señeris et al., 2022). It thrives under Type A climate conditions as classified by Schmidt and Ferguson, characterized by an annual rainfall of 2000–3000 mm, 150–200 rainy days per year, and temperatures between 20 and 30°C. Abaca can grow in both lowland and highland areas, up to 1000 meters above sea level, and prefers loose, soft-textured, sandy soils (Balai Penelitian Tembakau dan Tanaman Serat, 1998).

Natural fibers are abundant, sustainable materials that offer advantages such as low cost, lightweight properties, renewability, biodegradability, and high specific strength (Habibie et al., 2021). Abaca fibers, particularly those obtained from the stalk segments fused with the leaf sheaths, are known for their exceptional durability and mechanical strength (Barba et al., 2020). Abaca fibers are known for their high tensile strength, moisture resistance, and long fibrous morphology with micro-scale diameters, making them highly suitable for sound wave attenuation (Khotimah et al., 2014).

This study introduces an innovative material termed Abaca-wool, engineered from abaca fibers processed into a form resembling natural wool or rockwool. The resulting material exhibits a porous and flexible structure. The name "Wool" refers to the wool-like morphology of the final product, albeit derived from plant-based fibers. Abaca-wool was developed to explore the potential of abaca as a natural sound absorber that combines acoustic efficiency with environmental sustainability.

To evaluate the acoustic performance of Abaca-wool, this research employed a quantitative approach using two primary methods. First, the sound absorption coefficient was measured using an impedance tube in accordance with ASTM E1050-12. This method provides accurate data across a wide frequency range under controlled laboratory conditions. Second, numerical simulations were conducted using AFMG SoundFlow software. This tool employs the wave characteristic method for porous media to model acoustic behavior based on key material parameters such as porosity, airflow resistivity, and material thickness. It enables high-precision prediction of sound absorption performance and serves as a complementary analysis to experimental results (AFMG, n.d.).

While previous studies have explored the acoustic properties of various natural fibers, there remains a notable gap in the literature concerning the comprehensive characterization of abaca fibers, particularly in a processed wool-like form (Taiwo et al., 2019). Most existing research has focused on traditional abaca composites or unmodified fibers, without examining their performance as fibrous absorbers similar to mineral wool (Indrawati et al., 2024). Furthermore, there is limited integration of both experimental measurement and numerical simulation in evaluating the acoustic behavior of such natural materials. This study addresses these gaps by introducing and characterizing Abaca-wool, a novel fibrous absorber derived from abaca fibers, through a dual-method approach combining impedance tube measurements and acoustic modeling. By providing detailed acoustic data and simulation validation, this research contributes new insights into the development of sustainable, high-performance sound-absorbing materials based on underutilized natural resources.

The primary objective of this research is to investigate the acoustic potential of Abaca-wool through both experimental and numerical methods, and to compare the results to assess the validity and consistency of the material's performance. The findings of this study are expected to contribute to the advancement of sustainable acoustic materials and promote the broader application of natural fibers in acoustic engineering.

METHODS

This study employed an experimental methodology combined with quantitative and simulation-based approaches to evaluate and model the sound absorption characteristics of a novel natural fiber-based material, namely Abaca-wool. The process began with the preparation of abaca (Musa textilis) fibers, which were cut into 5 cm lengths as illustrated in Figure 2. These fibers then underwent an alkali treatment using a 15% sodium hydroxide (NaOH) solution for two hours at room temperature, as shown in Figure 3. The purpose of this chemical treatment was to remove hemicellulose and lignin content, enhance surface roughness, and purify the fibers into predominantly cellulose structures.

Following the alkali treatment, the fibers were thoroughly rinsed under running water until a clean and coarse texture was achieved, indicating a reduction in non-cellulosic compounds. The fabrication of Abaca-wool was carried out in two refining stages. In the first stage, the fibers were blended with water for 100 seconds using a standard kitchen blender (wet refining method). The resulting pulp was then dried in an oven at 175°C for one hour. In the second stage, the dried fibers underwent dry refining using a mechanical chopper for 100 seconds to produce a texture similar to mineral wool. The final product, as shown in Figure 4, served as the primary test material. The samples were molded into circular specimens with a bulk density of the Abaca-wool sample was 0.078 g/cm³, with a thickness of 27 mm and a diameter of 3 cm using a specialized mold under a compressive load of 610 Pa.

Figure 4. Abaca fibers cut into 5 cm lengths

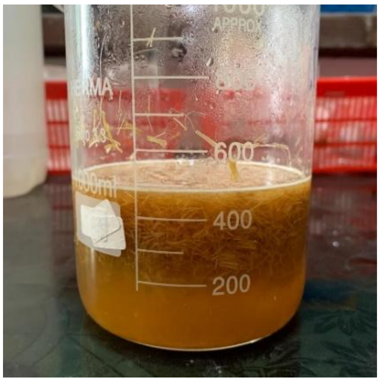


Figure 2. Soaking process of abaca fibers in 15% NaOH solution for 2 hours

Figure 3. Abaca-wool fibers

To analyze the morphological structure of the material, high-resolution digital microscopy was performed at the Materials Laboratory, Department of Physics, Institut Teknologi Sepuluh Nopember (ITS), Surabaya. The digital microscope, equipped with an integrated camera and analytical software, enabled real-time observation and measurement of morphological parameters, such as fiber diameter. The Abaca-wool samples were placed under the objective lens, illuminated by LED light, and visualized on a monitor screen to document and analyze the fiber surface images. This morphological data is crucial in understanding the relationship between microstructure and acoustic performance.

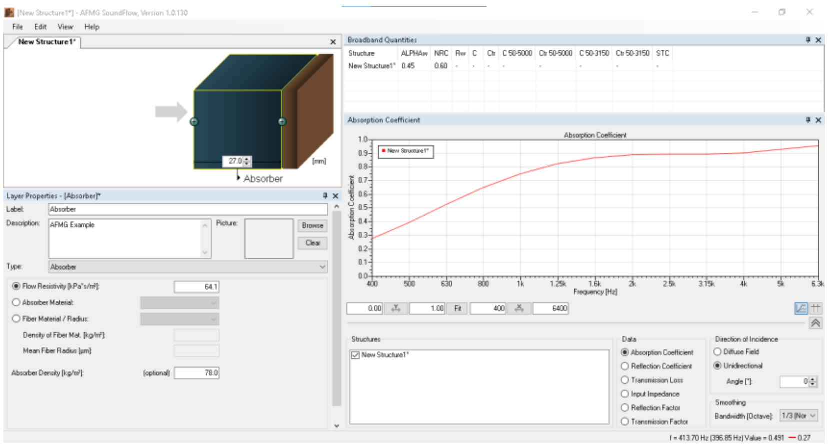


Figure 5. Abaca-wool sound absorption simulation using AFMG SoundFlow software

Subsequently, for the purpose of simulation using AFMG SoundFlow software, as illustrated in Figure 5, the physical parameters of Abaca-wool were measured. These included thickness, density, porosity, and airflow resistivity. Thickness was measured using a precision ruler, while density was calculated using a densimeter and pycnometer based on the standard density equation. Airflow resistivity was estimated using an empirical formula that incorporates porosity and density values. The sound absorption coefficient was determined using both simulation and experimental methods. The simulation was conducted via AFMG SoundFlow software, which models the acoustic absorption behavior of porous materials using input data such as porosity, airflow resistivity, and material thickness.

Figure 6. Abaca-wool testing using an impedance tube with a diameter of 3 cm

To validate the simulation results, experimental testing was performed using the impedance tube method in accordance with ASTM E1050-12 standards, as shown in Figure 6. In this procedure, the sample was placed at one end of the tube, with a sound source at the opposite end generating acoustic waves in the frequency range of 400–6400 Hz (1/3 octave bands). Microphones positioned at specific points inside the tube recorded the sound pressure of incident and reflected waves, from which the sound absorption coefficient was calculated. The experimental tests were conducted using the Abaca-wool samples at the acoustic laboratory facilities, Faculty of Mathematics and Natural Sciences, Universitas Negeri Sebelas Maret.

RESULTS AND DISCUSSION

Fiber Structure and Morphology Analysis

The development of natural fiber-based sound-absorbing materials, such as Abaca-wool, requires a comprehensive understanding of fiber structure and morphology, as these characteristics play a critical role in determining the acoustic performance of the material. In this study, abaca fibers (*Musa textilis*) underwent a series of treatments aimed at enhancing their acoustic properties.

The initial stage involved cutting the abaca fibers into 5 cm lengths, followed by an alkaline treatment using a 15% sodium hydroxide (NaOH) solution for two hours at room temperature. The selection of a 15% NaOH concentration and a soaking duration of two hours was based on previous studies demonstrating its effectiveness in significantly reducing lignin and hemicellulose content without causing substantial degradation of cellulose. Bledzki and Gassan (1999) and John and Thomas (2008) reported that this concentration is optimal for enhancing fiber surface roughness and cellulose exposure while maintaining the mechanical integrity of natural fibers (Gassan & Bledzki, 1999; John & Thomas, 2008). Moreover, Mamtaz et al. (2016) observed that alkali treatment at this concentration leads to a reduction in fiber diameter due to the removal of non-cellulosic components and moisture, which facilitates subsequent processing and improves interfacial bonding in composite applications (Mamtaz et al., 2016).This chemical process was designed to remove lignin and hemicellulose content, thereby increasing the cellulose concentration in the fibers. As a result of this treatment, the fiber surfaces became rougher and more homogeneous, as observed under a high-resolution digital microscope. The increased surface roughness enhances the specific surface area, which promotes greater interaction between the material and incident sound waves, facilitating improved conversion of acoustic energy into heat through viscoelastic friction.

Subsequent to the chemical treatment, the fibers were subjected to a wet refining process using a blender for 100 seconds, followed by oven drying at 175°C for one hour. A final dry refining stage using a mechanical chopper for another 100 seconds produced a fiber structure that closely resembles mineral wool. The resulting fibers were randomly entangled, forming a porous and complex network. Digital microscopy revealed that individual fibers had an average diameter of 1.46×10^{-5} m or 14.6 μm , as shown in Figure 7.

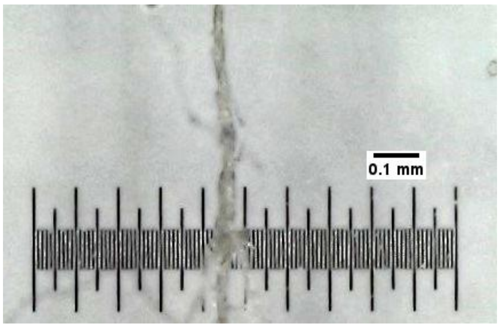
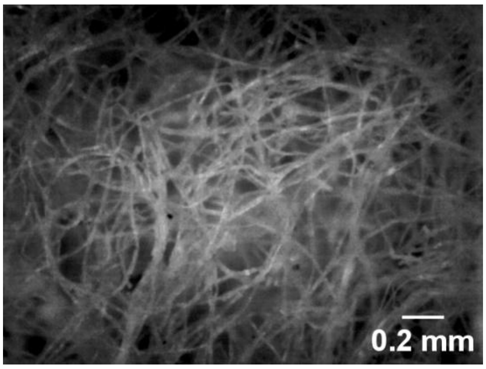


Figure 7. Morphological analysis of Abaca-wool fibers showing an average fiber diameter of 1.46×10^{-5} m or 14.6 μm.



Gambar 8. Morphological structure of Abaca-wool panel with a thickness of 27 mm and a bulk density of 0.078 g/cm³.

For comparison, sheep wool fibers typically have diameters ranging from 17–25 μm, depending on the breed (Rey et al., 2017), while cotton fibers measure approximately 16–20 μm. Coconut fibers, on the other hand, are significantly coarser, with diameters ranging from 100–450 μm (Kabir et al., 2012). In contrast, mineral fibers such as rockwool and glasswool usually have diameters between 3–10 μm (H. Yang et al., 2007), and synthetic fibers like polyester can be engineered to have diameters in the range of 10–20 μm. With a diameter of approximately 14 μm, abaca wool fiber exhibits a fineness comparable to that of mineral fibers in terms of micron-scale dimensions, while retaining the essential characteristics of natural fibers, such as biodegradability and material sustainability. This distinctive combination supports the justification for utilizing abaca wool as a bio-based alternative for sound-absorbing materials.

The discrepancy between the fiber and bulk densities indicates the presence of considerable inter-fiber voids, yielding a porosity of 93%. This high porosity, also depicted in Figure 8, plays a crucial role in the acoustic behavior of the material, allowing for effective sound wave penetration and dissipation via internal friction and conversion of sound energy into heat.

The airflow resistivity value of 64,117 kPa·s/m² was estimated using an empirical model proposed by Kozeny-Carman (1957), which relates fiber diameter and bulk density to airflow resistivity in fibrous materials. This indirect calculation was employed due to the absence of specialized equipment for direct measurement. The average fiber diameter, determined via optical microscopy, and the bulk density of the Abaca-wool sample served as input parameters to the model(Cozeny-Carman, 1956). This relatively low value suggests that the material offers minimal resistance to airflow, a desirable trait for sound-absorbing materials.

In summary, the structural and morphological properties of Abaca-wool, achieved through combined chemical and mechanical treatments, significantly contribute to its acoustic performance. The material's high porosity, rough fiber surface, and optimal airflow resistivity establish Abaca-wool as a promising candidate for sustainable and environmentally friendly sound-absorbing applications.

Acoustic Properties and Comparative Analysis with AFMG SoundFlow Simulation Results

The acoustic performance of the sound-absorbing material was evaluated using two complementary approaches: experimental measurements employing a two-microphone impedance tube and numerical simulations using the AFMG SoundFlow software. The tested sample consisted of a Abaca-wool, with a bulk density of 78.5 kg/m³ and a total thickness of 27 mm. Figure 9 presents the sound absorption coefficient (α) as a function of frequency in the range of 500–6400 Hz for both scenarios: experimental measurement and numerical simulation.

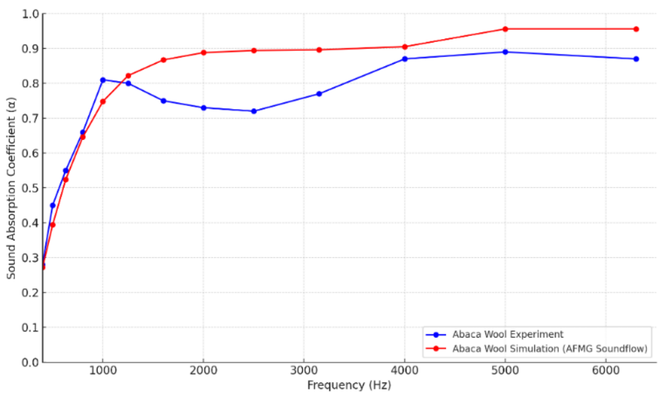


Figure 9. Comparison of the sound absorption performance of Abaca-wool obtained from impedance tube measurements (blue curve) and AFMG SoundFlow simulations (red curve).

The experimental results in Figure 9 show a sharp increase in the absorption coefficient at low frequencies, reaching the first peak at approximately 1000 Hz with α ≈ 0.83. This is followed by a decline in performance within the frequency range of 1500–2500 Hz, and then a gradual increase in absorption, approaching α ≈ 0.89 at frequencies above 4500 Hz.

The prominent peak observed at around 1000 Hz can be attributed to the unique morphological characteristics of the Abaca-wool material. As previously discussed, its highly porous and randomly entangled fiber structure (porosity ≈ 93%) creates complex micro-acoustic pathways that enhance viscoelastic friction between air molecules and fiber walls. At 1000 Hz, the wavelength of sound in air is approximately 34 cm—roughly 12–13 times the panel thickness (2.7 cm)—which aligns with optimal conditions for destructive interference and energy conversion in open-porous media (T. Yang et al., 2020).

The observed dip in absorption around 2500 Hz may be attributed to (1) local resonance effects not supported by the fiber structure at that frequency, and (2) the material's airflow resistivity (64,117 kPa·s/m²), which may limit wave penetration and cause impedance mismatch (Rodríguez et al., 2022). Additionally, based on quarter-wavelength theory, absorption decreases when the material thickness is close to one-fourth of the incident wavelength. At ~2500 Hz, this condition is met, potentially triggering resonance effects that reduce viscous losses and sound energy dissipation(Allard et al., 2005; Geslain et al., 2011).

The subsequent increase in α at high frequencies (>3500 Hz) is likely driven by the dominance of internal friction mechanisms and dynamic energy dissipation. The microstructure of Abaca-wool—resembling mineral wool—provides an appropriate level of resistance against high-frequency air oscillations, thereby enhancing sound attenuation (Bravo-Moncayo et al., 2024).

Numerical simulations conducted using AFMG SoundFlow, with identical input parameters : airflow resistivity (64,117 kPa·s/m²), density (78.5 kg/m³) and thickness(3 cm) derived from the experimental data, exhibited a closely matching trend. The absorption coefficient also rose at low frequencies, peaking at α ≈ 0.9, and remained consistently high at mid to high frequencies. However, unlike the experimental results, the simulation did not exhibit a significant dip around 2500 Hz. Instead, it produced a smoother and more stable response curve.

This discrepancy can be explained from two scientific perspectives. First, simulation models generally adopt a linear and homogeneous approach to material structure, which does not fully account for micro-scale heterogeneity such as pore size distribution, surface roughness, and fiber diameter variability. In practice, Abaca-wool exhibits localized structural variations due to its manual fabrication process, which may introduce internal diffraction effects or localized acoustic impedance zones at specific frequencies (Raj et al., 2021).

Second, boundary factors such as micro-acoustic leakage and viscous skin effects along the inner walls of the impedance tube may influence experimental outcomes, leading to deviations that are not captured by the simulation. These imperfections contribute to minor differences between experimental and simulated results, as the latter assumes ideal boundary conditions and uniform material behavior (GmbH, 2021).

To quantitatively assess the deviation between simulated and experimental results, the Root Mean Square Error (RMSE) was calculated. This statistical metric captures the average magnitude of squared deviations between the simulated absorption coefficients generated by AFMG SoundFlow and those measured experimentally using the impedance tube method.

For the standalone Abaca-wool fiber sample, the RMSE was found to be 0.089. Given the absorption coefficient range (α) between 0 and 1, this corresponds to an average prediction error of approximately 8.9%, indicating a high degree of agreement between the simulated and experimental data. This result validates that the physical parameters used in the simulation—such as airflow resistivity, porosity, and material thickness—were well calibrated and representative of the actual conditions, particularly in the mid-frequency range. The relatively simple structure of the pure fiber sample also contributes to the model's accuracy, as it aligns more closely with the assumptions made in the simulation framework.

Despite these differences, the overall agreement between the experimental and simulated curves, particularly in terms of trend and peak values of α, indicates that the AFMG SoundFlow simulation is a reliable tool for predicting the acoustic performance of natural fiber-based materials, provided that the input parameters are accurately calibrated using empirical dat

CONCLUSION

This study investigated the potential of a novel bio-based acoustic material, Abaca-wool, through experimental and numerical methods to assess its sound absorption performance. The engineering process involved chemically treating abaca fibers with 15% NaOH to enhance cellulose content and surface roughness, followed by refining steps to form a mineral wool-like microstructure. The resulting material exhibited high porosity (~93%), an airflow resistivity of 64.117 kPa·s/m², and low bulk density, indicating strong acoustic potential. Its randomly oriented hollow microfibers created complex pathways for sound, enhancing internal friction and energy dissipation, which was confirmed by impedance tube tests showing peak absorption coefficients of ~0.89 at high and ~0.83 at mid frequencies (~1000 Hz). Numerical simulations using AFMG SoundFlow closely matched experimental trends, with minor deviations at ~2500 Hz due to model limitations, but overall confirmed the material's performance when calibrated with empirical data. Abaca-wool thus shows strong promise as a sustainable, biodegradable, and non-toxic alternative to synthetic acoustic materials.Given its lightweight nature and effective mid-to-high frequency absorption, Abaca-wool has promising potential for implementation in green buildings, classroom ceilings, recording studios, and other indoor environments requiring eco-friendly acoustic treatment.

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