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Sound Absorption Characteristics of Polyurethane Composites with Nanocellulose from Oil Palm Empty Fruit Bunches

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Abstract
This study explores the sound absorption behavior of polyurethane-based composites reinforced with nanocellulose derived from oil palm empty fruit bunches. Nanocellulose was synthesized through chemical and mechanical processes and incorporated into the polyurethane matrix at weight ratios of 3%, 5%, 10%, and 20%. Test specimens were prepared with standardized dimensions and evaluated using a four-microphone impedance tube system following ASTM E2611-19 to determine the frequency-dependent acoustic response across the 125–5000 Hz range. The results demonstrated a clear improvement in sound absorption in the mid-to-high frequency bands (1000–4000 Hz) as nanocellulose content increased, with peak absorption coefficients (α) exceeding 0.7 at frequencies above 3000 Hz for 5% and 10% formulations. This enhancement is attributed to increased tortuosity, airflow resistivity, and complex internal structures formed by the nanocellulose fibers. However, performance in the low-frequency range (100–1000 Hz) remained limited across all compositions, and excessive filler loading (20%) led to diminishing returns due to particle agglomeration and reduced pore connectivity. These findings suggest that oil palm empty fruit bunch nanocellulose holds substantial potential as a sustainable acoustic reinforcement material, particularly for high-frequency applications. Further structural optimization is recommended to expand its applicability for broadband noise control.
Keywords: *nanocellulose, oil palm empty fruit bunches, sound absorption*

1. INTRODUCTION

Noise pollution, particularly in urban and industrial settings, is an escalating environmental concern that has wide-ranging effects on human health and the ecosystem [1][2]. Excessive noise, often referred to as bising, can cause hearing impairment, sleep disturbances, stress, and cardiovascular diseases, while also impacting wildlife behavior and biodiversity [3][4]. One common source of noise pollution is industrial machinery, transportation systems, and dense urban environments [5][6].

Nanocellulose, a high-aspect-ratio biopolymer derived from lignocellulosic biomass, offers distinct advantages such as low density, high surface area, tunable porosity, and biodegradability [7][8][9]. These characteristics make it highly attractive for acoustic, packaging, biomedical, and structural applications [10][11]. Recent studies have emphasized its versatility in forming highly porous and mechanically robust structures suitable for sound damping and energy dissipation applications [12][13][14][15]. In particular, cellulose nanofibers (CNFs) and cellulose nanocrystals (CNCs) extracted from agricultural residues—such as oil palm empty fruit bunches (OPEFB or TKKS)—have demonstrated significant potential as functional fillers in acoustic and structural composites [16][17]. OPEFB, a by-product of palm oil production, is abundant in Indonesia and other Southeast Asian countries, representing a valuable renewable resource for nanocellulose production [18][19] Several studies have reported the potential of nanocellulose-reinforced polymer composites for sound absorption applications [20][21]. When incorporated into polyurethane matrices, nanocellulose can modify pore morphology, enhance tortuosity, and increase airflow resistivity—key parameters influencing sound dissipation [22][23]. For example, proven acoustic damping in nanocellulose-enhanced PU foams, particularly in the mid-to-high frequency range [24] linked increased nanofiber content with enhanced scattering and friction-induced dissipation within the matrix [10][25].

The growing demand for sustainable materials in acoustic insulation has prompted significant interest in the development of bio-based polymer composites with enhanced sound absorption properties [26][2][11]. Among these, polyurethane (PU) has emerged as a widely utilized matrix due to its favorable combination of lightweight characteristics, ease of processing, and viscoelastic damping behavior [3][27]. However, conventional PU foams exhibit limited effectiveness in attenuating low-frequency sounds because of their inherent porous structure and inadequate thickness, which motivates structural or compositional modifications for improved broadband absorption [28][29] Recent studies have encoded promising strategies to bridge this limitation by integrating fillers or advanced structural configurations [30][31]. For instance, multilayered and graphene-oxide-impregnated PU foams have demonstrated ultra-broadband absorption capabilities, significantly improving mid-to-high frequency range via enhanced tortuosity and airflow resistivity [6][32]. Similarly, PU filled with multiple cavities (metastructures) or resonator-backed porous layers has generated additional low-frequency absorption peaks, verifying theoretical models such as those referenced in Johnson–Champoux–Allard frameworks [33][34].

Despite these advancements, incorporating bio-based fillers—especially cellulose nanofibers or nanocrystals—remains attractive for achieving sustainable, efficient acoustic composites [35][36]. Nanocellulose offers a unique combination of high surface area, tunable porosity, and renewability, with recent reviews highlighting its potential in eco-friendly acoustic materials [30][37]. Notably, several studies report that filler addition effectively improves mid-frequency absorption (400–1600 Hz) in PU composites, though challenges persist in reinforcing low-frequency performance without targeted macrostructural design methods [20][38]. Building on this background, the present study investigates the frequency-dependent acoustic behavior of polyurethane composites reinforced with varying concentrations (3%, 5%, 10%, and 20%) of nanocellulose derived from oil palm empty fruit bunches Using impedance tube measurements spanning 125–5000 Hz and analysis based on standard ASTM protocols, we aim to identify the optimal filler loading that balances sustainability, microstructural efficiency, and practical acoustic performance across the mid-to-high frequency spectrum [18][39].

Despite the promise of such composites, the challenge remains in achieving effective low-frequency absorption, typically requiring macrostructural design interventions such as multilayer configurations, cavity backing, or hybrid assemblies [22][23]. The role of filler concentration is also critical: while moderate loadings enhance performance, excessive nanocellulose content may lead to agglomeration and reduced pore connectivity, adversely affecting sound attenuation[25][40]. The present study investigates the acoustic behavior of PU-based composites reinforced with varying concentrations (3%, 5%, 10%, and 20%) of TKKS-derived nanocellulose [41][42]. Using the impedance tube method compliant with ASTM E2611-19, sound absorption coefficients were measured across a frequency range of 125–5000 Hz [43][44]. The objective is to determine the optimal filler loading for improved mid-to-high frequency performance while identifying limitations in the low-frequency domain. By focusing on a sustainable filler source and its functional integration into PU matrices, this work contributes to advancing green materials for noise control technologies.performance while identifying limitations in the low-frequency domain[45]. By focusing on a sustainable filler source and its functional integration into PU matrices, this work contributes to the advancement of green materials for noise control technologies [46].

2. METHOD

Materials

The pineapple leaf fiber (Ananas comosus) utilized in this study was obtained from agricultural plantations located in Kampar Regency, Pekanbaru, Riau, Indonesia. The chemical reagents employed included distilled water (aquadest), 30% sodium hydroxide (NaOH), and 30% hydrogen peroxide (H_2O_2), all of which were sourced from EMD Millipore Corporation, Germany.

1. Nanocellulose Preparation and Pre-Treatment

Nanocellulose used in this study was extracted from oil palm empty fruit bunches (TKKS) through a combination of chemical and mechanical processes. The TKKS fibers were initially cut into 1–5 cm segments and boiled to remove residual impurities. The pre-treatment involved a three-step chemical process: alkali treatment, bleaching, and acid hydrolysis. The alkali treatment was carried out using 2 wt% NaOH at 70°C for 3 hours to remove lignin and non-cellulosic materials. This was followed by a bleaching process with 4 wt% NaOH and 7.2 wt% H_2O_2 at 55°C for 2 hours to achieve further purification.

The resulting cellulose was then diluted to 1% concentration and processed mechanically through high-shear grinding or ultrasonication. This step was essential to reduce the cellulose fibers to nanoscale dimensions, enabling better dispersion within the polyurethane matrix and enhancing surface interactions for acoustic applications.

2. Composite Fabrication and Sample Preparation

The nanocellulose produced was mixed with polyurethane at varying weight ratios (3%, 5%, 10%, and 20%) to study its influence on sound absorption characteristics. Each formulation was thoroughly mixed to ensure homogeneity and then poured into molds to produce cylindrical test specimens. All samples were fabricated with a diameter of 100 mm and a thickness of 5 mm, specifically designed for evaluating sound absorption in the low-frequency range. After curing at room temperature, the specimens were removed from the molds and prepared for acoustic testing. The aim of this process was to assess the effectiveness of TKKS nanocellulose as a reinforcement agent for enhancing the sound absorption capability of polyurethane-based materials. **The initial stages of nanocellulose extraction, including lignification and bleaching, are illustrated in Figure 1.** The fabrication process is illustrated in Figure 1. The physicochemical and morphological characterization of TKKS-derived nanocellulose, including FTIR, SEM, and XRD analyses, were performed separately and are presented in a companion publication. Therefore, this study exclusively focuses on evaluating the acoustic absorption performance of the polyurethane–nanocellulose composites across a frequency range of 125–5000 Hz using the impedance tube method.

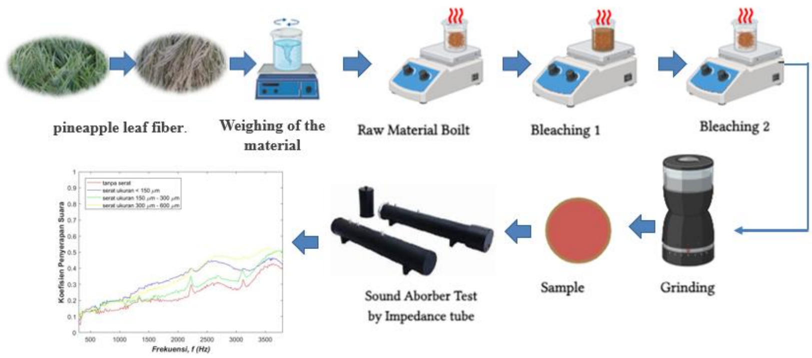

Figure 1. Lignification and bleaching process

3. Acoustic Testing Setup

The acoustic properties of the TKKS nanocellulose–polyurethane composites were evaluated using a **Brüel & Kjær (B&K) Impedance Tube system**, model **SCS9020B/K** from **Controlli e Sistemi (SCS)**, operated at **Universiti Tun Hussein Onn Malaysia (UTHM)**. The experimental protocol adhered to the **ASTM E1050-2** standard, which governs normal incidence sound absorption coefficient measurements using the transfer-function method, as illustrated in **Figure 2**

The test apparatus comprised the following components:

• A rigid cylindrical impedance tube constructed from precision aluminum, ensuring minimal vibrational interference and acoustic leakage.

• A signal generation system delivering controlled sinusoidal waveforms into the tube via a calibrated loudspeaker.

• Two fixed microphones, positioned at designated locations along the tube's length to measure incident and reflected acoustic waves.

• A dedicated signal acquisition system connected to digital analysis software developed specifically for the SCS9020B/K unit.

Measurements were carried out over a frequency range of 1600 Hz to 6000 Hz, focusing on mid-to-high frequency acoustic response. The environmental test conditions were precisely monitored: air density at 1.2 kg/m³, temperature at 2.2°C, relative humidity at 67%, and atmospheric pressure at 101.20 kPa.

Figure 2. Acoustic impedance tube test setup used at UTHM (Model SCS9020B/K).

This system provided accurate data on how the nanocellulose filler content influenced the sound absorption performance of the composite, particularly within the mid-to-high frequency domain. The resulting sound absorption coefficient (α) values offered insight into the effectiveness of fiber–matrix interactions in dissipating acoustic energy.

3. RESULTS

This section presents and analyzes the acoustic performance of polyurethane composites reinforced with varying concentrations of TKKS-derived nanocellulose. The experimental results obtained from impedance tube testing are discussed in relation to the material's microstructural characteristics and their influence on sound absorption behavior across different frequency ranges. Each formulation is evaluated based on its ability to attenuate low, mid, and high-frequency sound waves, followed by a comparative interpretation grounded in established acoustic absorption models.

1. **Sound Absorption Control Material**

The sound absorption coefficient (α) of the TKKS nanocellulose–polyurethane composite, as measured using an impedance tube, exhibits a clear frequency-dependent behavior driven by the material's porous architecture. At low frequencies (100–1000 Hz), absorption remains below 0.3, highlighting the composite's limited effectiveness in attenuating long-wavelength sound due to insufficient thickness and pore depth. The addition of nanocellulose alone is not adequate to overcome these structural limitations without macro-scale design interventions, such as multilayering or cavity backing. In the mid-frequency range (1000–2500 Hz), absorption improves markedly, reaching α ≈ 0.45 around 1800 Hz. This enhancement is attributed to the presence of interconnected pores and fibrous nanocellulose, which facilitate viscous and thermal losses. The increased tortuosity and airflow resistivity arising from the nanocellulose–polyurethane interaction significantly contribute to this improved performance.

At high frequencies (2500–4000 Hz), the material demonstrates its peak acoustic efficiency, with α values exceeding 0.6 and peaking near 0.75. This high-frequency attenuation results from enhanced internal scattering, multiple reflection pathways, and the synergistic damping effect between the nanocellulose network and the polyurethane matrix. These results align with predictions from the Johnson–Champoux–Allard porous media model, wherein high tortuosity and specific airflow resistivity yield superior sound absorption at elevated frequencies. While the composite excels in the 2000–4000 Hz range, its performance remains frequency-selective rather than broadband. Thus, further design enhancements—such as gradient porosity, multilayer construction, or hybrid configurations with resonant structures—are recommended to extend its absorption capability into the lower frequency spectrum, as illustrated in Figure 2

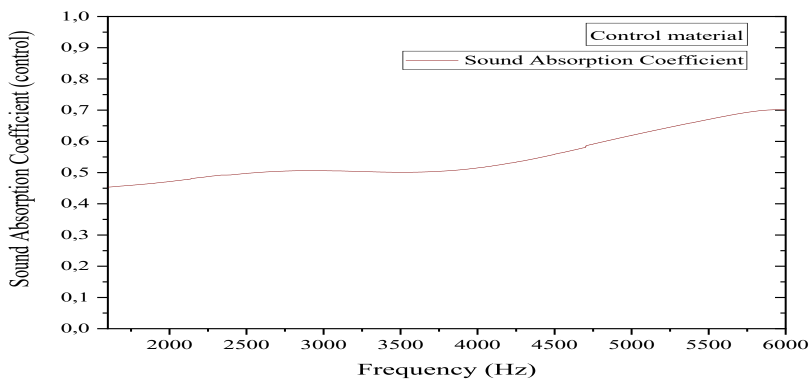

Figure 2. Sound absorption coefficient graph before TKKS nanocellulose addition

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2. Effect of 3% TKKS Nanocellulose Addition on the Acoustic Performance of Polyurethane Composite

The acoustic characterization of the TKKS nanocellulose–polyurethane composite with 3% filler content reveals a frequency-dependent sound absorption profile indicative of its microstructural behavior. At low frequencies (100–1000 Hz), the absorption coefficient (α) remains below 0.25, which is typical for porous and fibrous materials with limited thickness and tortuosity. This poor performance in the low-frequency domain stems from insufficient energy dissipation due to shallow pore structures and restricted viscous and thermal losses. As the frequency increases beyond 1200 Hz, a gradual improvement is observed, with α reaching approximately 0.4–0.45 around 1800 Hz. This suggests enhanced sound–structure interaction, likely due to micro-resonance and scattering mechanisms facilitated by the dispersed nanocellulose fibers. The 3% filler concentration contributes to moderate increases in tortuosity and internal surface area, promoting more efficient acoustic energy attenuation in the mid-frequency range, as shown in Figure 3.

In the high-frequency region (2500–4000 Hz), the composite exhibits peak absorption values, with α exceeding 0.6 and approaching 0.7 near 3500 Hz. This performance is attributed to the synergistic effects of the polyurethane matrix and the nanoscale cellulose fibers, which together form a complex internal network that enhances acoustic dissipation through scattering and reflection. These results are consistent with the Johnson–Champoux–Allard model, which links sound absorption efficiency to porosity, airflow resistivity, and frame tortuosity. Overall, the material demonstrates high efficacy in the mid-to-high frequency range, making it suitable for applications such as interior soundproofing, architectural acoustic panels, automotive damping, and electronics insulation. However, its limited low-frequency performance suggests a need for structural enhancement—such as the integration of multilayer systems, backing cavities, or resonant components—to enable broader frequency coverage and improved noise control.

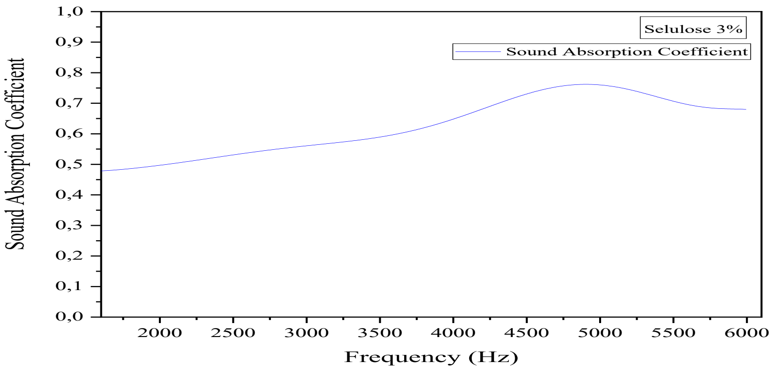

Figure 3. Sound absorption coefficient graph with 3% TKKS nanocellulose addition

3. Effect of 5% TKKS Nanocellulose Addition on Polyurethane-Based Acoustic Composite

The acoustic evaluation of the TKKS nanocellulose–polyurethane composite with 5% reinforcement reveals a frequency-dependent absorption profile shaped by the interplay between the bio-based filler and the polyurethane matrix. At low frequencies (100–1000 Hz), the sound absorption coefficient (α) remains below 0.3, with limited energy dissipation observed, particularly below 800 Hz. This outcome is consistent with the known behavior of porous absorbers, where long-wavelength sound is insufficiently attenuated due to inadequate thickness and pore depth. Although the 5% nanocellulose inclusion slightly enhances tortuosity and airflow resistivity, these improvements are insufficient to impact performance in this regime substantially. In contrast, the mid-frequency range (1000–2500 Hz) demonstrates a marked increase in absorption, with α values approaching 0.5 around 2000 Hz. This is attributed to enhanced internal damping and scattering facilitated by the fibrous nanocellulose network, which offers an optimal balance between filler dispersion and composite density—favorable conditions for mid-frequency attenuation, as illustrated in Figure 4.

In the high-frequency range (2500–4000 Hz), the composite achieves peak performance, with α exceeding 0.65 and reaching up to 0.72 above 3000 Hz. This enhanced high-frequency response is driven by the synergy between the polyurethane's open-cell structure and the complex acoustic pathways introduced by nanocellulose fibers, which promote sound wave entrapment and dissipation. Compared to 3% or 10% formulations, the 5% composite displays a well-balanced absorption profile across mid-to-high frequencies, avoiding excessive filler agglomeration while preserving effective pore connectivity. These results align with established models such as Delany–Bazley and Biot–Allard, which associate increased tortuosity and airflow resistivity with improved acoustic efficiency. Practically, the 5% nanocellulose-reinforced composite is suitable for mid-to-high frequency noise control in applications like vehicle cabin panels, interior architectural elements, office partitions, and HVAC system enclosures. To extend performance into lower frequencies and achieve broader acoustic bandwidth, future designs may incorporate multilayer configurations, perforated facings, or integrated backing cavities.

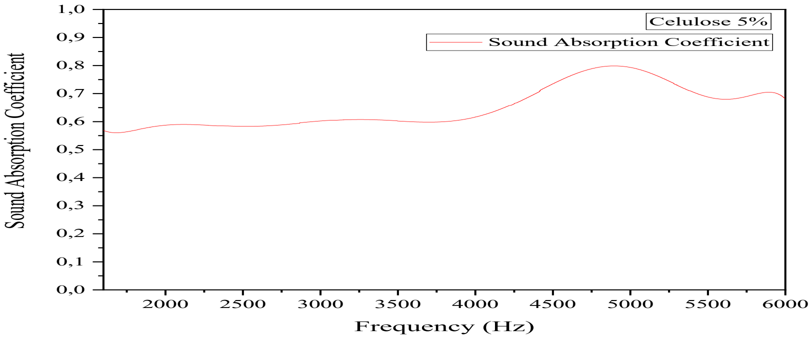

Figure 4. Sound absorption coefficient graph with 5% TKKS nanocellulose addition

4. Effect of 10% TKKS Nanocellulose Addition on Polyurethane Composite Properties

The acoustic characterization of the polyurethane-based composite reinforced with 10% TKKS-derived nanocellulose demonstrates a frequency-dependent sound absorption profile with significant improvements across the mid-to-high frequency spectrum. At low frequencies (100–1000 Hz), the material exhibits limited absorption, with α remaining below 0.3, which is typical for porous materials where sound wavelengths exceed the material thickness. Nonetheless, a gradual increase in α is observed starting around 800 Hz, suggesting that the additional nanocellulose enhances airflow resistivity and internal friction modestly. In the mid-frequency range (1000–2500 Hz), performance improves more substantially, with α surpassing 0.5 near 1800 Hz. This improvement is attributed to increased tortuosity and a more entangled microstructure resulting from the denser distribution of nanocellulose fibers that facilitate viscous and thermal dissipation mechanisms. Compared to lower filler ratios, the 10% formulation achieves a more effective balance between structural complexity and acoustic responsiveness, as depicted in Figure 5.

The composite achieves its peak performance in the high-frequency range (2500–4000 Hz), with α reaching up to 0.78 at approximately 3500 Hz. This enhanced efficiency is primarily due to the high surface-area-to-volume ratio of nanocellulose and its well-dispersed fibrous network, which creates multiple reflection paths and micro-resonance effects that trap and attenuate short-wavelength sound energy. The acoustic behavior aligns well with established porous media models, including the Biot–Allard and Johnson–Champoux–Allard frameworks, where energy dissipation improves with higher tortuosity and airflow resistivity. Compared to composites with lower nanocellulose content (e.g., 3%), the 10% variant shows a rightward shift and amplification of the absorption peak, indicating enhanced high-frequency performance. However, caution must be taken regarding potential filler agglomeration, which could reduce uniformity and acoustic efficiency at higher concentrations. This material is particularly well-suited for high-frequency noise mitigation in architectural spaces, studio environments, and electronic enclosures. To broaden its absorption capability into the low-frequency range, future research may consider hybrid structures, multilayer systems, or embedded resonant components.

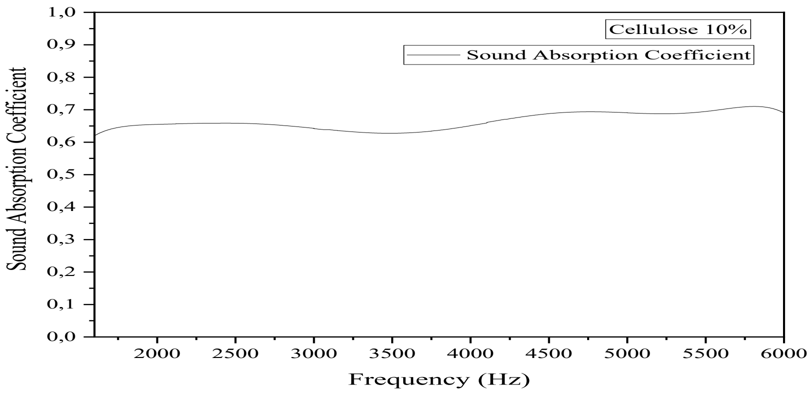

Figure 5. Sound absorption coefficient graph with 10% TKKS nanocellulose addition

5. Effect of 20% TKKS Nanocellulose Addition on the Properties of Polyurethane Composite

The acoustic response of the polyurethane composite reinforced with 20% TKKS-derived nanocellulose reveals distinct frequency-dependent absorption behavior influenced by the material's enhanced porosity, tortuosity, and internal damping characteristics. At low frequencies (100–1000 Hz), the sound absorption coefficient (α) remains below 0.25, reflecting the typical limitation of porous and fibrous materials in attenuating long-wavelength sound due to insufficient thickness and pore geometry. Despite the increased filler content, structural constraints persist in this regime unless complemented with resonance-based or cavity-enhanced designs. In the mid-frequency range (1000–2500 Hz), the absorption coefficient rises to approximately 0.45–0.5 around 1800–2000 Hz, attributed to the denser internal matrix and higher flow resistivity introduced by the 20% nanocellulose loading. However, the rate of increase is more gradual than in composites with lower filler content (e.g., 5% or 10%), likely caused by fiber agglomeration and reduced effective pore connectivity, which hinders optimal acoustic energy dissipation, as illustrated in Figure 6.

In the high-frequency domain (2500–4000 Hz), the composite achieves its peak performance, with α exceeding 0.65 and reaching around 0.73 above 3200 Hz. This strong absorption is facilitated by complex microstructural pathways and increased surface area, promoting extensive scattering and multiple micro-reflection events. However, further increases in nanocellulose content beyond 20% may compromise uniformity, causing matrix stiffening and pore obstruction that reduce overall acoustic efficiency. The observed trends align with theoretical models such as the Johnson–Champoux–Allard and Biot–Allard frameworks, which associate higher frame tortuosity and airflow resistivity with improved absorption—though diminishing returns become evident at excessive filler levels. Compared to composites with 3%, 5%, or 10% nanocellulose, the 20% formulation displays a broader absorption peak at upper-mid to high frequencies but with lower sharpness and reduced mid-frequency gains. This highlights a trade-off between filler concentration and structural dispersion. Given these characteristics, the 20% nanocellulose composite is most suitable for high-frequency noise control in enclosed spaces, studio paneling, and electronics insulation. For enhanced broadband performance, future research should explore hybrid formulations, multilayered structures, or macrostructural enhancements such as gradient foams and grooved sandwich panels.

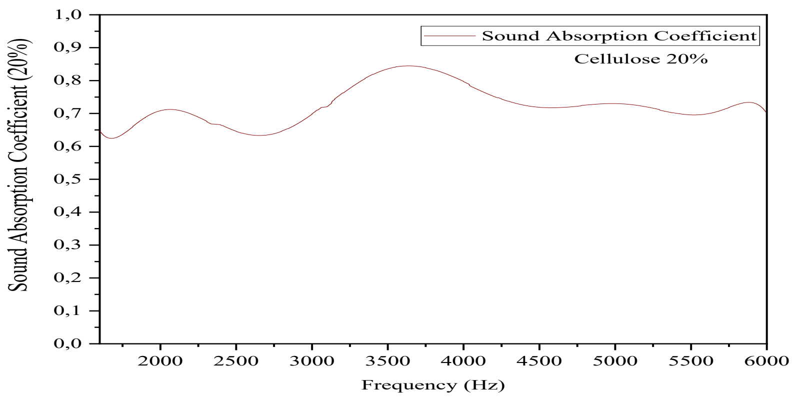

Figure 6. Sound absorption coefficient graph with 20% TKKS nanocellulose addition

4. CONCLUSION

This study investigated the frequency-dependent acoustic behavior of polyurethane-based composites reinforced with nanocellulose derived from oil palm empty fruit bunches (TKKS). Impedance tube measurements revealed that the addition of TKKS nanocellulose significantly enhanced sound absorption in the mid-to-high frequency range (1000–4000 Hz). However, its performance in the low-frequency range (100–1000 Hz) remained limited across all filler concentrations. Composites with 5% and 10% nanocellulose content exhibited the most balanced acoustic response, achieving peak absorption coefficients (α) exceeding 0.7 at frequencies above 3000 Hz.

These improvements were attributed to increased tortuosity, enhanced airflow resistivity, and complex microstructures formed by the nanocellulose fibers. However, higher filler concentrations (e.g., 20%) led to agglomeration and reduced pore connectivity, limiting further performance gains. TKKS nanocellulose has demonstrated significant potential as a bio-based reinforcement material for sustainable acoustic insulation. Future work should focus on structural optimization—such as multilayer configurations, gradient porosity, or integration with resonant systems—to extend sound absorption capabilities to lower frequency bands and broaden its applicability in architectural, automotive, and electronic noise control systems.

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