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RESEARCH ARTICLE

Effects of oil palm frond fiber reinforcement on morphology, mechanical, and acoustic properties of rigid polyurethane foam

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Abstract – The quest for innovative, eco-friendly materials has spurred the exploration of agricultural biomass waste as a potential resource for polymer composites. The current study examines the impact of untreated oil palm frond (OPF) fiber on the multifunctional and sustainable performance of rigid polyurethane (PU) foam in the oil palm industry, in alignment with Sustainable Development Goals 12 and 13. Using a one-shot polymerization method, OPF foams were fabricated with fiber contents of 0, 5, 10, 20, and 30 (wt%). The foams were tested for density, morphology, compressive strength, and sound absorption performance in accordance with ASTM D1621 and ISO 10534-2. Experimental densities were compared with theoretical values to confirm that the foam production process was consistent. Scanning electron microscopy analysis revealed that OPF contents above 20 wt% disrupted the cellular structure, resulting in non-uniform cell sizes and increased cell wall collapse. These morphological defects contributed to a reduction in compressive strength from 0.1901 N/mm² for neat PU foam to 0.0697 N/mm² at 30 wt% OPF. In contrast, the 30 wt% OPF foam showed greater porosity and a higher proportion of open cells, resulting in superior sound absorption performance in the 1000–2500 Hz frequency range. Overall, the findings reveal a clear trade-off between mechanical strength and acoustic efficiency. PU foams with high OPF content possess eco-sustainable benefits and enhanced sound-absorbing qualities. Despite the reduction in compressive strength, high OPF-loaded PU foams show potential for lightweight, non-structural applications, such as automotive parts and interior building materials.

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1. Introduction

Environmental and public health issues stemming from noise pollution have intensified due to rapid industrialization and urbanization. Prolonged noise exposure can lead to stress, sleep disturbances, high blood pressure, and cognitive dysfunction. These adverse health effects are driving significant demand for effective acoustic materials, particularly in the construction and transportation industries. All petroleum-based foams, glass fibers, and mineral wool are considered conventional noise absorbers, are very efficient at sound absorption, and have strong acoustic properties. However, they are all non-biodegradable and require energy to produce foams, which ultimately leads to environmental issues [1-3]. To address such issues, scholars have considered using renewable agro-based fibers to bolster polymer composites. Natural fibers are promising because they are widely available, inexpensive, biodegradable, and have good strength-to-weight ratios [4-7]. In polymer composites, the mechanisms of sound-like energy absorption have been improved with the addition of fibers such as sisal, jute, bagasse, coir, and sugar cane [8-11]. For instance, Abdel-Hamid et al. [12] demonstrated that sisal-reinforced PU foams increased tensile and yield strength with increasing sisal content, while Othmani et al. [13] reported that sugar-cane-bagasse-filled PU foams achieved improved airflow resistivity and mid-frequency damping. Likewise, Bhingare and Prakash [14] found that coir-based composites showed high sound absorption coefficients, while Ahsan et al. [15] observed that tea-leaf-fiber foams combined reduced density with increased absorption efficiency. All these studies show that fiber morphology, especially the lumen structure, aspect ratio, and surface roughness, can affect energy dissipation and interfacial flow in porous, biodegradable foams. Among various agro-fibers, oil-palm frond (OPF) fiber is an abundant but underutilized by-product of the palm oil industry in Southeast Asia. Each hectare of plantation generates several tonnes of frond waste annually, which is usually left to decay or burned in the field, contributing to environmental pollution [16-18]. Converting this biomass into functional composite fillers supports waste valorization and circular-economy objectives. Kuranchie et al. [19] reviewed bio-based polyurethane (PU) foams reinforced with agro-wastes and highlighted that filler content, particle size, and fiber–matrix adhesion critically influence the balance between mechanical strength and acoustic efficiency. Similarly, Zhao et al. [20] demonstrated that bio-derived porous composites exhibit tunable thermal and sound-insulation behavior depending on fiber dispersion and foam morphology. However, systematic data on the influence of OPF fiber content on the mechanical and acoustic characteristics of rigid PU foams are limited.

Rigid PU foam is widely used as an acoustic material owing to its open-cell structure, low density, and ease of fabrication [21-23]. The inclusion of natural fibers such as OPF has the potential to further enhance its mechanical integrity and, potentially, sound-damping capacity while reducing reliance on petroleum-derived components [24-25]. Such developments align with the automotive industry's push toward lightweight, sustainable, and eco-efficient materials for interior noise control and structural applications. Accordingly, this study aims to evaluate the combined effects of OPF fiber loading (0–30 wt%) on the physical, mechanical, and acoustic performance of rigid PU foams. The

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investigation focuses on density, compressive strength, cell morphology, and sound absorption coefficient across different frequency ranges, in accordance with ASTM D1621 and ISO 10534-2. The novelty of this work lies in quantifying the mechanical–acoustic trade-off associated with OPF incorporation and establishing design guidelines for sustainable sound-absorbing materials suitable for automotive and architectural applications. The research contributes to advancing renewable-fiber composites in noise-control technology and supports Sustainable Development Goals 12 (Responsible Production and Consumption) and 13 (Climate Action).

2. Materials and Methods

2.1 Materials

The fibers used in this research were extracted from 10-year-old oil palm trees (*Elaeis guineensis*), which were grown in Riau, Indonesia. After pruning, the palm fronds were removed from the trees, and the fibrous midribs were separated from the leaf blades and sheaths, as shown in Figure 1. The separated leaf blades and sheaths were cleaned and sun-dried for 48 hours. A miter saw was then used to cut the fronds into smaller pieces, followed by additional sun drying for another 72 hours to reduce the moisture content to approximately 10%. This moisture level ensured sufficient stiffness and dimensional stability during the grinding stage. A disc mill was used to grind the dried material, which was subsequently sieved through a 40-mesh screen (≈ 0.42 mm) to obtain fibers of the same size for the complete integration with the PU matrix. Singh et al. and Khalid et al. have suggested such fibers to yield a better dispersion with reduced clumping [26-27]. No chemical treatment was applied to the fibers in this study. The use of untreated OPF was intentional to preserve the natural lignocellulosic structure and demonstrate a fully eco-friendly reinforcement approach with minimal processing energy. Future research may investigate alkaline or silane surface treatments to enhance interfacial adhesion between fiber and polymer matrix. Rigid PU foam was prepared using polypropylene glycol (PPG 1000) and methylenediphenyl diisocyanate (MDI), both supplied by Sutindo Chemical Indonesia. The chosen polyol and isocyanate collectively impart the toughness and long-term stability normally sought in structural grades of the polymer. Distilled water served as the blowing agent, generating gas *in situ* and expanding the matrix during polymerization. All raw materials carried standard industrial-grade certification and were used as received, minimizing variability from pre-treatment or batch alteration. This practice facilitates the reproducibility of experimental results reported in the study.

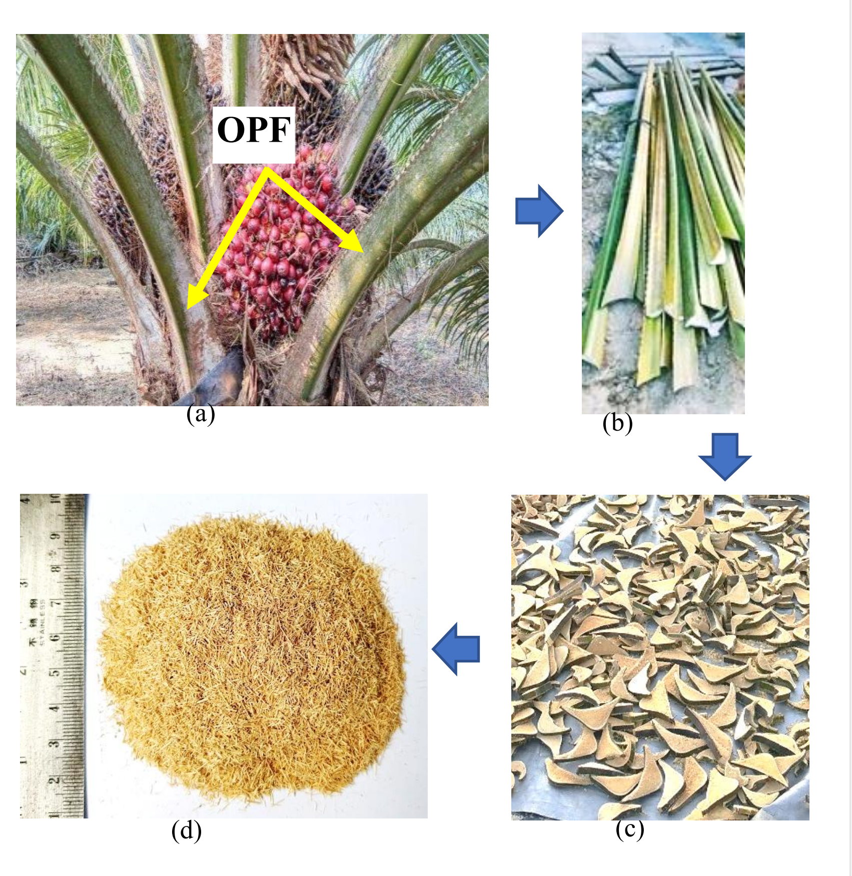

Figure 1. Oil palm frond fiber: (a) Plant, (b) Palm fronds, (c) OPF chips, (d) OPF fiber (40 mesh)

2.2 Preparation of PU/OPF Composites

PU foams were synthesized using a conventional one-shot method, in which a premix of Component A-catalyst, propylene glycol, surfactant, and deionized water was first prepared. An equal mass of liquid MDI was then blended into the polyol pool at a 1:1 stoichiometric ratio, yielding a rigid foam of moderate density. For composite formulations, oil palm fibers were dry-blended into the polyol mixture prior to the addition of isocyanate at loadings of 5, 10, 15, 20, 25, and 30 wt%.

The resulting slurry was poured into box molds where it rose freely and cured at room temperature. Specimens that exhibited the best strength and stiffness were routed to sound-absorption evaluation, examined microscopically, and weighed to record their true density. Individual variants were coded OPF-0 through OPF-30 to reflect the precise level of reinforcement. A flow diagram illustrating the production sequence is presented in Figure 2.

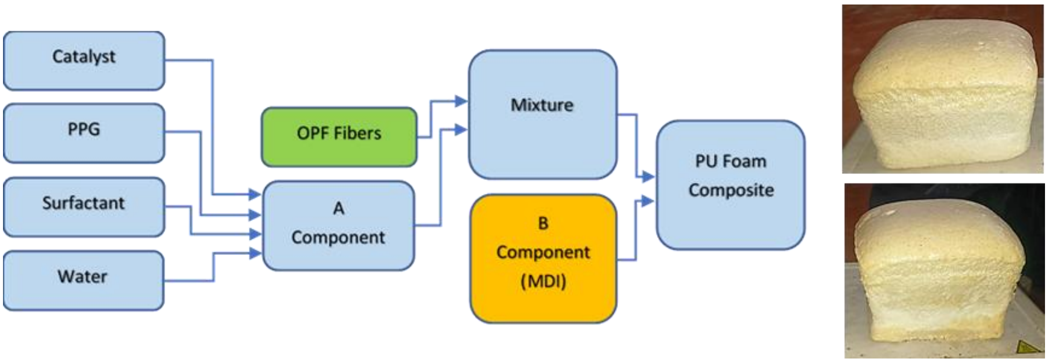

Figure 2. Synthesis process of biofiber-based PU composites

2.3 Density Measurement

Density (ρ_a) of each composite specimen was measured using a digital density meter (MD300S, Alfa Mirage, Japan), which determines mass and volume simultaneously based on Archimedes' principle. Each reported value represents the mean of three readings. The theoretical density (ρ_t) was calculated by the rule of mixtures using the known densities of the polyurethane matrix and OPF fibers. The deviation between experimental and theoretical densities was within ±3 %, confirming high measurement consistency. All procedures followed ASTM D1622 (2021) for rigid cellular plastics.

2.4 Compressive Strength Test

Compressive strength testing on the composite materials was carried out using a Shimadzu Autograph 20 kN universal test machine, as pictured in Figure 3(d). The procedure followed ASTM D1621 and ensured consistency with a widely accepted framework for rigid cellular plastics. Prismatic specimens with dimensions of 50 × 50 × 26 mm were compressed at 0.26 mm/s until failure occurred. The mean values of three replicates were reported along with the corresponding standard deviation. Additional mechanical properties, such as hardness, bending, and impact strength, were not evaluated in this phase and are reserved for future investigation to establish comprehensive structure-property relationships. The specimens subjected to compressive strength testing are depicted in Figure 3.

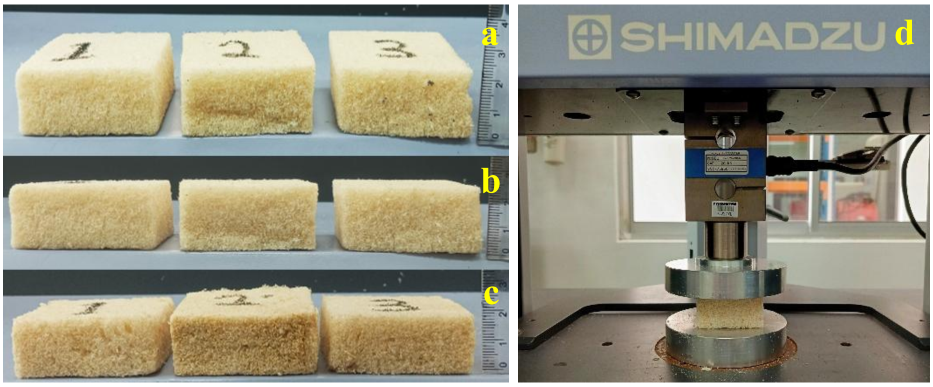

Figure 3. Samples after compressive strength testing: (a) Neat PU; (b) 5% OPF; (c) 30% OPF; (d) Shimadzu Autograph 20 kN Universal Testing Machine

2.5 Morphological Characterization

FESEM (Hitachi SU5000) images were taken at 50–100× magnification. Gold–palladium sputter coating (Quorum Q150R) was applied to improve conductivity. Foam cell size, distribution, and fiber dispersion were analyzed from the obtained micrographs.

2.6 Acoustic Performance Evaluation

The evaluation of sound absorption properties was determined from the two-microphone method impedance tube following ISO 10534-2:1998 and ASTM E1050-98 standards. These procedures are relatively consistent in measuring the acoustic properties of materials and obtaining valid results. Only samples exhibiting the highest and lowest mechanical performance were discussed in detail to highlight the differences between the most and least effective formulations and to better understand factors that influenced mechanical strength and the behavior of the samples under failure. Circular specimens with a diameter of 33 mm were prepared to meet the dimensional requirements of the testing standards. As shown in Figure 4, all samples were cut to uniform thickness and surface area to yield more consistent results in measuring the sound absorption. Sound absorption tests were conducted over a frequency range of 500 Hz to 4500 Hz. The composite material's performance was summarized using the noise reduction coefficient (NRC), which distills the frequency-dependent absorption curve into a single, dimensionless value. For the present study, the NRC was computed as the arithmetic mean of absorption coefficients recorded at 250, 500, 1000, and 2000 Hz [28]. The NRC was calculated using Eq. (1).

$$NRC = \frac{\alpha 250 + \alpha 500 + \alpha 1000 + \alpha 2000}{4} \tag{1}$$

where *α250, α500, α1000*, and *α2000* refer to the sound absorption coefficients measured at 250, 500, 1000, and 2000 Hz, respectively. Each *α* value conveys how much acoustic energy a given medium retains at its matching frequency.

Figure 4. Samples prepared for sound absorption test

3. Results and Discussion

3.1 Compressive Strength Of OPF/PU Composites

Based on Figure 5, increasing the OPF fiber results in a continuous decrease in the maximum pressure of the PU composite. As the sample population increases from 0% to 30%, the maximum stress decreases from 0.1901 N/mm² to 0.0697 N/mm². Statistically, this trend can be represented by a linear equation with a slope of -0.0040 N/mm². This clearly indicates that the reduction in compressive strength is due to increased OPF loading. A number of factors may influence the above phenomenon. Weak interface bonding between the hydrophilic OPF fibers and the relatively hydrophobic PU matrix is attributed to be the main cause. The absence of interfacial adhesion inhibits the proper transfer of the stress applied to the matrix and fibers, which causes early failure mechanisms such as fibers being pulled out and matrices cracking under certain loads. This phenomenon has been widely reported in reinforced composites utilizing lignocellulosic fibers that lack surface treatment or compatibility agents.

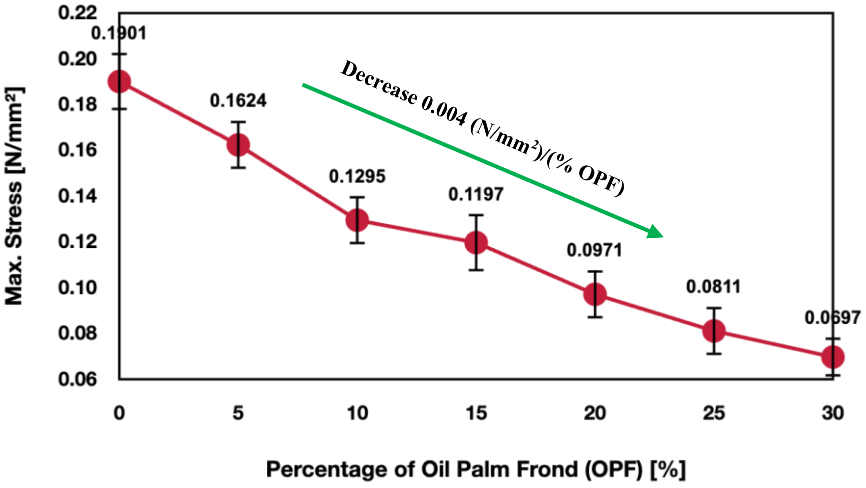

Figure 5. Effect of different filler loadings of OPF on the compression strength of PU composite foams

In addition, elevated OPF concentration might give rise to microstructural defects like fiber clumping and the formation of microcracks due to insufficient mixing into the polymer matrix. These defects serve as stress intensifiers and weaken the structural framework supporting the structure [29]. The stiffness mismatch between OPF fibers and the PU matrix may further exacerbate stress localization at the fiber–matrix interface, diminishing the composite's ability to withstand tensile forces [30-31]. At higher filler contents, particularly at 30% OPF, pronounced effects of filler interactions and fiber agglomeration were observed. These interactions formed volumes of concentrated and localized stress that prompted cell walls to rupture and collapse with adjacent cells. The weak interfacial adhesion of the hydrophilic OPF fibers and hydrophobic PU matrix worsened the effect to the point that during compression, poor stress transfer caused the compressive strength to drop to 0.0697 N/mm². Other studies have highlighted similar trends, where the agglomeration of natural fibers at extreme loadings led to poor mechanical properties due to structural inhomogeneities [32-33]. The error bars in Figure 5 account for discrepancies within the measurements. This response is expected within composite materials due to the slight variations in fiber distribution, mixing, or the conditions under which the testing was carried out. Nevertheless, the general trend is apparent: increased OPF content results in weaker composites. From a practical perspective, a balance must be achieved between incorporating natural fillers such as OPF fibers for sustainable development and maintaining the composite's mechanical performance. While OPF incorporation lessens the cost of materials and the impact on the environment, excessive OPF content may weaken the composite to a point that it may not be useful for structural applications. Based on these results, OPF contents below 10-15% appears to be a better trade-off between strength and sustainability.

3.2 Densities of OPF/PU Composites

The densities of the composites were evaluated due to their influence on the mechanical and acoustic properties of PU foams. The densities of PU composite foams with differing fiber loading are shown in Figure 6. Foam density depends on the amount of solid material forming the foam network, the density of the polymer matrix, and the density of the gas within the cells. The incorporation of OPF fibers altered the foam's cellular structure, leading to a reduction in overall density compared with neat PU foam. The presence of fibers increased void formation and disrupted uniform cell growth, thereby decreasing the mass per unit volume. Although fillers may occasionally raise density by occupying empty spaces, OPF fibers in this study acted as nucleation sites that hindered cell coalescence and promoted the formation of larger, irregular pores, which ultimately resulted in lower density for the OPF-reinforced rigid PU foams.

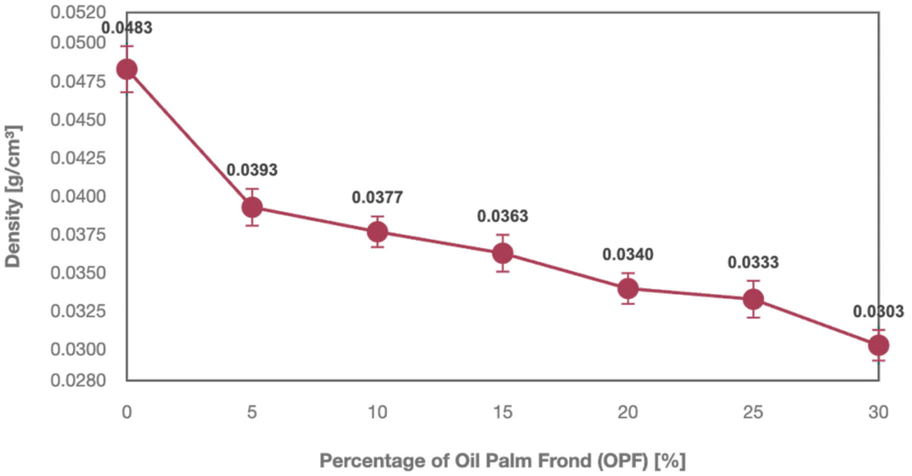

Figure 6. Density of PU-OPF composites with different OPF filler loadings

The density of the rigid PU–OPF composites exhibited a clear decreasing trend with increasing OPF content, as shown in Figure 6. The highest density was recorded at 0% OPF with 0.0483 g/cm³, declining gradually to 0.0303 g/cm³ at 30% OPF. This decline in density is consistent with the changing density observed in the scanning electron microscopy (SEM) images in Figure 7. Neat PU foam (0% OPF) exhibited a relatively closed-cell, dense, and homogeneous structure, accounting for its higher density and compressive strength of 0.1901 N/mm². With the incorporation of OPF content, larger and more irregular cells were observed with thin cell walls and evidence of fiber clumping. At 30% OPF, the foam structure exhibited severe cell damage and loss of cellular order, which may explain the mechanical weakness and low compressive strength (0.0697 N/mm²). The decrease in density is attributed to the interference of OPF fibers that limits foam expansion, leading to lower polymerization efficiency and weaker cell formation. Poor fiber–matrix bonding further weakened the cellular structure, limiting effective cell formation and resulting in less mechanically robust foams. Similar observations have been widely reported, where reduced cell integrity leads to lower density and diminished mechanical performance [32]. With respect to fiber from oil palm, noise reduction benefits are counterbalanced by internal inconsistencies that reduce compressive strength and general solidity, with marked deterioration in performance present beyond a fiber volume fraction from 10% to 15% due to the bio-based characteristics. The concurrent decrease in both density and maximum stress with increasing OPF content suggests a strong interrelationship between these two properties. As density decreases, structural integrity and load-bearing capacity of the material are compromised. This phenomenon can be attributed to the inherent properties of OPF, which, while contributing to sustainability, may not provide similar mechanical performance as other traditional materials. The findings of this study highlight the dual impact of OPF incorporation on both density and mechanical strength. The reduction in density may enhance certain properties, such as lightweight characteristics, but compromises maximum stress resistance.

3.3 Morphology Analysis

The SEM image of the control sample exhibited a smooth and homogeneous surface, indicative of a neat PU matrix without fiber reinforcement, as shown in Figure 7(a). The absence of fibers suggests limited mechanical reinforcement, leading to a higher compressive strength. In Figure 7(b) and 7(c), the addition of 5% and 30% OPF fibers, respectively, results in noticeable changes in surface morphology. Morphological analysis of the PU foam composites with varying OPF fiber content was performed using an FESEM (Hitachi SU5000). The morphology of neat PU foam (Figure 7(a)) shows a closed-cell structure with well-defined pores. The foam cell walls are smooth, and the internal voids are filled with air. This indicates that the foam structure is intact and exhibits normal foam rheology. However, the composite containing 5% OPF (Figure 7(b)) exhibits noticeable distortion of the cell walls of the foam. The cell walls were ruptured, and the cell pore morphology appears elongated. The cell structure became more irregular with cell sizes deviating from a normal pore hierarchy, with measured pore diameters ranging from approximately 218 µm to 729 µm. At 30% OPF loading (Figure 7(c)), a complete loss of cell structure is evident. The cell walls appear fragmented, the foam polymer becomes increasingly fibrous, and the cells are coarser. The findings of compressive strength are consistent with the findings from the morphometric analysis. As shown in Fig. 5, increasing OPF fiber content corresponds to a substantial reduction in compressive strength, decreasing from 0.1901 N/mm² for neat PU foam to 0.0697 N/mm² at 30 wt% OPF—a reduction exceeding 63%. Highly degraded foam loses its structural integrity and is morphologically compromised. This poor fiber dispersion results in the formation of large, irregularly shaped cells and walls that are either too thin or completely torn. Such defects may establish structural weaknesses that act as mechanical stress concentrators.

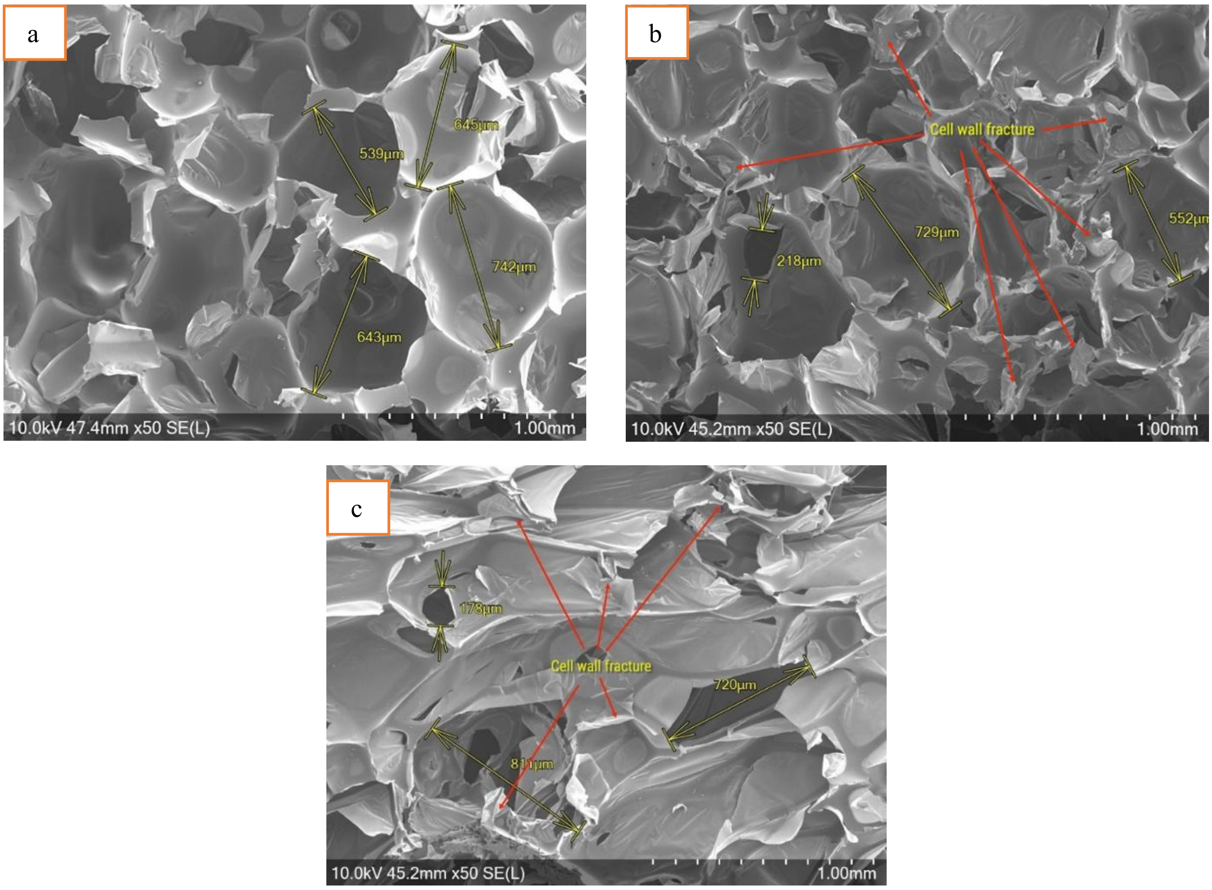

Figure 7. Fractured morphology and cell size distribution of PU/OPFs composites foams: (a) 0 wt%; (b) 5 wt% and (c) 30 wt%

These observations align with existing literature on lignocellulosic fiber-reinforced PU foams. For instance, Kurańska et al. [34] observed that high filler loadings of natural fibers in PU matrices resulted in open-cell structures, poor fiber–matrix adhesion, and significant reductions in compressive strength due to voids and weak interfacial zones. Similarly, Kuranchie et al. [19] demonstrated that natural fillers, including hemp shives, increased foam heterogeneity and reduced compressive strength when added beyond an optimal level due to the mismatch in surface energy between fibers and the PU matrix. Prociak et al. [35] demonstrated that an overabundance of fiber can stifle bubble expansion and precipitate premature rupture of the cell wall, thereby weakening the material's mechanical robustness. When natural fibers are added in large quantities, poor adhesion between the fibers and matrix often leads to clumping, creating localized stress risers where cracks can first appear under compression. However, higher fiber loading may lead to more intricate composite architecture, and voids that remain within the matrix hint at inadequate bonding between the two phases. Strong interfacial adhesion remains essential for ensuring that loads are transmitted effectively across the composite during mechanical testing [36-37]. The current study proposes the addition of approximately 5% fiber content to provide an optimal balance between mechanical reinforcement and overall stability of the foam structure. Further analysis indicated that the absence of effective nucleation was the primary cause of the highly irregular distribution of cell size throughout the composite. High-magnification SEM images confirmed that exceeding a certain level of filler content resulted in porous structures with a wider cell size distribution, whereas lower loadings produced a narrower distribution. This trend appears to correspond perfectly with the compressive strength, which demonstrates a clear cause-and-effect relationship between fine structure and overall strength [38-39]. Overall, PU foams produced from OPF fibers exhibit enlarged pore structures and new pore architecture irregularities when fiber addition is increased. Conversely, reduced filler fraction results in a tighter cell geometry due to more effective nucleation, leading to improved load dissipation and enhanced compressive strength.

3.3 Sound Absorption Properties

The sound absorption performance of PU composites reinforced with OPF fibers is presented in Figure 8, which plots the sound absorption coefficient (α) over a frequency range of 500–4500 Hz for three formulations: 0%, 5%, and 30% OPF. A notable shift in acoustic behavior is evident with increasing fiber content. The α–frequency curves demonstrate enhanced absorption in the 1–2.5 kHz range with increasing OPF. The sound absorption coefficient is substantially affected by the type and characteristics of the reinforcement materials [16, 40-41]. The neat PU foam (0% OPF) demonstrates maximum absorption of sound ($\alpha > 0.9$) within the high-frequency range of 2000–2500 Hz. This performance is typical of rigid PU foams exhibiting closed-cell morphology, where higher-frequency sound waves are effectively attenuated by the vibrations of the cell walls and the air friction within the pore spaces. With the introduction of OPF fibers, the absorption characteristics change noticeably. At 5% OPF, the absorption profile becomes broader and multiple peaks are identified within the range of 1000–2200 Hz, indicating enhanced absorption performance in the mid-frequency region. The presence of OPF fibers is hypothesized to facilitate performance by partially opening cell walls and increasing surface area. This, as was noted from the micrographs, was confirmed via SEM observations. The disrupted cellular morphology further leads to viscous and thermal losses through multiple reflections and heterogeneous scattering of sound waves within the porous PU structure. Peng et al. [42] describe this phenomenon in natural fiber sound absorbers with open-cell morphology foams. At 30% OPF, the absorption profile continues to flatten with its peak shifting to lower frequencies, and maintains an α of 0.5–0.6, indicating a midway absorption performance for a much wider frequency range. The highly disrupted pore structure and increased porosity enhance airflow resistivity, which is beneficial for sound absorption at lower frequencies However, the diminished absorption peak intensity suggests lesser resonance and acoustic impedance matching, which could be ascribed to a number of large macro-pores as well as poor material cohesion reported by Khaleel et al., who noted comparable results in bio-based acoustic foams with a high degree of fiber loading [43].

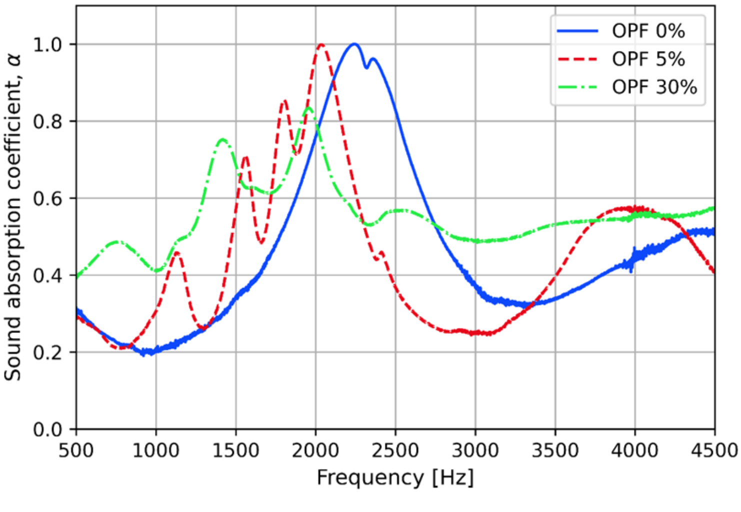

Figure 8. Sound absorption coefficient - frequency graph for OPF fiber-reinforced PU foam composites and neat PU foam

The findings highlight a trade-off between mechanical integrity and acoustic performance. Higher OPF contents allow for a greater range of acoustic absorption due to the porosity of tissue morphology. However, increased porosity leads to a decrease in compressive strength. Higher porosity also decreases the compressive strength further. The fibrous morphology of the OPF fibers is primarily what allows for the room on the surface to dissipate absorbed sound energy, as well as improving the acoustic performance through increased interfacial surface area [44]. This acoustic benefit is counterbalanced by a reduction in mechanical integrity, likely due to weakened cohesive interactions within the PU matrix at higher fiber contents [45, 46]. The enhanced absorption coefficients in fiber-reinforced composites may also be attributed to the expanded surface area at the filler-matrix interface, where acoustic energy is effectively converted into thermal energy [47, 48]. Furthermore, the presence of large, hollow lumens in the OPF fibers aids in sound absorption, consistent with the behavior of porous cellulose structures [49, 50]. The morphology and connectivity of the composite's cellular structure, specifically the presence of open, semi-open, or closed pores, also play a significant role in influencing overall acoustic performance [51, 52]. Therefore, for applications prioritizing sound insulation, such as automotive interiors or acoustic panels, higher OPF contents (e.g., 30%) may be more beneficial. Conversely, applications requiring mechanical robustness would favor lower fiber loading.

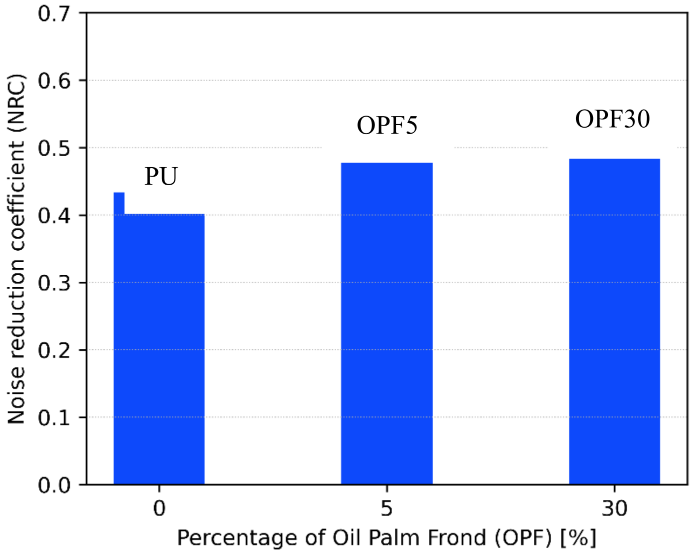

Figure 9. Noise reduction coefficient of OPF fiber-reinforced PU foam composites

The noise reduction coefficient values of PU foam composites containing different OPF fibers are shown in Figure **9**. The results indicate that sound absorption capacity improved when OPF fibers were added to the PU matrix. The control sample (0% OPF) exhibits an NRC of 0.43. When OPF fibers were added at 5% by volume, the OPF absorption level enhanced to 0.50, which represents a significant increase of 16 %. This enhancement supports the assumption that distributed OPF fibers negatively improve the cellular matrix of the PU foams to create more cells and more intercellular microchambers, which use energy to create reflections via friction to the absorbed sound [45,53-54]. Further increasing the OPF content to 30% results in only a marginal increase in NRC to 0.51. The minimal improvement compared to 5% OPF sample suggests that there is a reduction in the return on acoustic performance on higher fiber loadings. The plateau effect is likely due to fiber agglomeration and disruptions of the open-cell structure that may lead to a decline in the porosity and acoustic effectiveness of the material [45, 55]. The results show a trade-off between mechanical strength and sound absorption. Soundproof applications are recommended for these materials because the foam’s structural properties enhance acoustic insulation relative to weight and fracture resistance. Aside from sound mitigation, the current research indicates the inclusion of 5% OPF content represents a critical threshold, beyond which further increased dosages are likely lead to the loss of fibers’ mechanical integrity without significant gains in acoustic performance. This underscores the importance of optimizing fiber content to balance mechanical integrity and sound absorption effectiveness for practical applications.

3.4 Trade-off and Application Relevance

A distinct compromise between mechanical and acoustic characteristics is observed in OPF-reinforced PU foams. Increasing OPF content reduces compressive strength due to poor fiber-matrix adhesion and voids, while the same changes in morphology improve sound absorption by increasing open cell structures and increasing airflow resistivity. A 10-15 % OPF loading provides an optimal balance, maintaining sufficient mechanical strength while achieving effective sound absorption in the 1000–2500 Hz frequency range, which is particularly relevant for automotive interior noise control [56]. The same behavior has been reported in other bio-based PU composites, indicating that the inclusion of moderate amounts of natural fiber is effective in reducing mid-frequency damping [43, 44, 54]. Thus, in this fiber loading range, PU/OPF composites exhibit efficient damping characteristics and are well-suited as lightweight, eco-friendly material in the automotive and architectural industries.

4. Conclusions

This study examined the effects of incorporating untreated oil palm frond (OPF) fibers on the morphology, density, compressive strength, and sound absorption of OPF and polyurethane (PU) foams. The addition of OPF fibers altered the normal closed-cell structure of the neat PU foam into having a larger and more irregular pore structure, resulting in a lowered density from 0.0483 g/cm³ to 0.0303 g/cm³ at 30 % OPF. Compressive strength decreased from 0.1901 N/mm² to 0.0697 N/mm² as a result of weak interfacial bonding and fiber agglomeration. Notably, the increased openness of the foam structure positively correlated with sound absorption in the 1000–2500 Hz range, which is relevant to automotive interior frequencies. The strongest trade-off between structural soundness and sound absorption was observed at OPF contents between 10% and 15%. The study also demonstrates the potential to upcycle OPF waste into lightweight, sustainable PU-based composites for automobile noise insulation, in alignment with Sustainable Development Goals 12 and 13. Future work will focus on additional mechanical characterization (e.g., hardness and impact resistance) and surface treatments to further enhance the multifunctional performance of OPF-reinforced PU composites.

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Declaration of Competing Interest

The author declares no conflicts of interest.

CRediT Authorship Contribution Statement

B. Istana (Conceptualization; Methodology; Resources; Data curation; Writing - original draft; Resources)
J. A. Razak (Methodology; Resources; Supervision; Writing - review & editing)
A. Adriyan (Software; Visualization; Validation)
D. Prayuda (Formal analysis; Data curation)
R. Dai (Formal analysis; Data curation)

Availability of Data and Materials

The data supporting this study's findings are available on request from the corresponding author.

Ethics Declarations

This study did not involve human participants or animals. Ethical approval was therefore not required.

Generative Artificial Intelligence Declarations

The authors stated that generative AI was not used to generate content, ideas, or theories. We have just utilized AI to enhance readability and refine the language. This was used with extreme human control and oversight. The authors take full responsibility for reviewing and approving the content.

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